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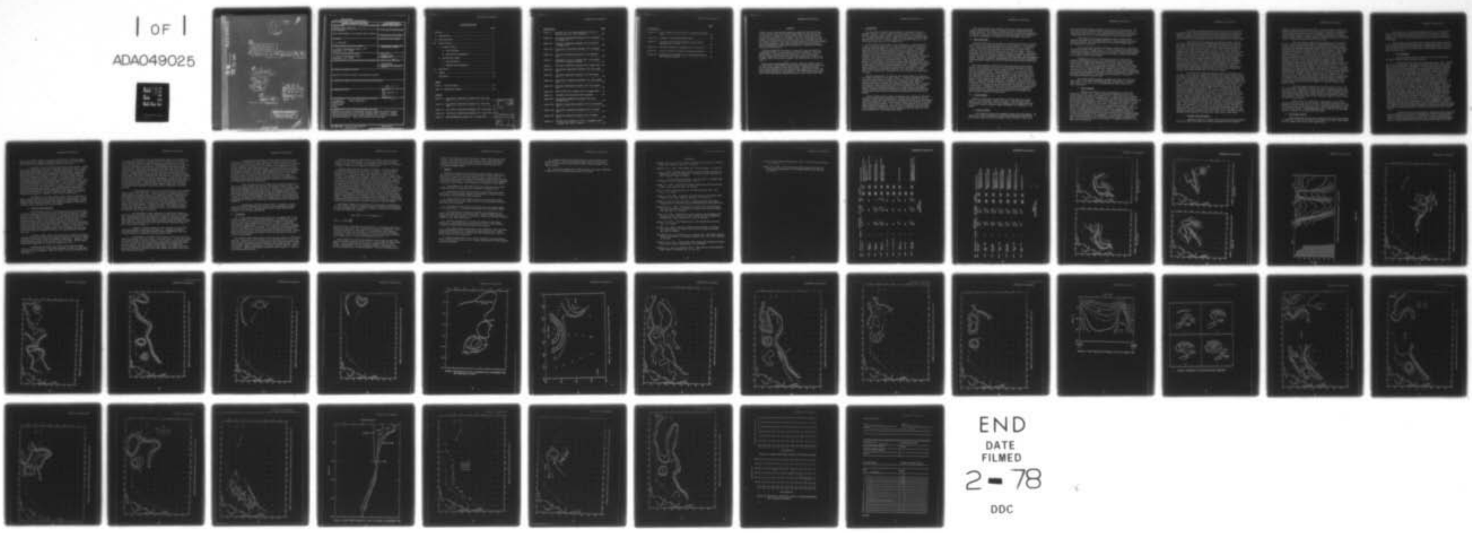

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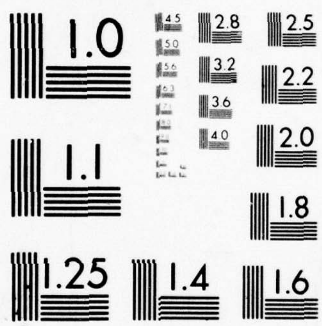
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Describes the results of 60 thermal structure eddies of the Gulf Stream between Cape Hatteras and 60°W from November 1969 to May 1973. Eddies were both cyclonic and anti-cyclonic and form east of 70°W from unstable Gulf Stream meanders. Their drift and decoy are described.

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## ABSTRACT

The results of 60 thermal structure studies of the Gulf Stream system from Cape Hatteras to 60°W between November 1969 and May 1973 are described. During this period sixteen Gulf Stream eddies were studied for periods of up to 8 months. The data indicated that both cyclonic and anticyclonic Gulf Stream eddies are an integral part of the thermal structure of the area, forming eastward of 70°W from unstable Gulf Stream meanders. Eddy sizes increase with eastward formation and once separated from the Gulf Stream maintain thermal and velocity structure efficiently.

Cyclonic eddies were observed to translate either westward in a spiraling path or on a more direct path to the southwest. Westward moving eddies coalesced with the Gulf Stream within five months. Cyclonic eddies not influenced by the Gulf Stream slowly subsided in Sargasso Water losing surface identity and drifting out of the survey area.

Anticyclonic eddies translate westward along the seaward edge of the Continental Slope. Early recapture of the eddies along this route by Gulf Stream meanders occurs east of 68°W. Anticyclonic eddies which remain unaffected by the Stream during translation re-enter the Gulf Stream northeast of Cape Hatteras. The eddies increase in speed west of 71°W and during translation exhibit a slow linear decay rate.

## I. INTRODUCTION

The term eddy as applied to oceanography is generally given to a circular movement of water formed in one of several ways: between adjacent currents, where currents pass obstructions, or along the edge of permanent boundary current. Eddy sizes can range from those which could be observed in a teacup to general circulation sizes such as the anticyclonic gyre known as the Sargasso Sea.

In the western North Atlantic, the Gulf Stream, a narrow boundary current, generates eddies as it courses eastward from Cape Hatteras to longitude 55°W and begins to lose identity as a current. Eastward of longitude 70°W Gulf Stream meanders increase in amplitude to a point where flow becomes unstable and eddies of mesoscale size are formed, ranging from 50 to 400 kilometers in diameter. Eddies form as the meanders, typically greater than 500 kilometers in wavelength, completely surround large masses of Slope or Sargasso Water much the same as an oxbow lake is formed on a meandering river. Newly separated eddies maintain an independent circulation through energy imparted by the Gulf Stream, rotating cyclonically or anticyclonically, depending upon whether a southward or northward extending meander crest is isolated. Cyclonic eddies composed of a cold core of Slope Water surrounded by an outer Gulf Stream ring are sometimes referred to as cold eddies or rings, while their anticyclonic counterparts may be referred to as warm eddies or rings.

Previous observations of mesoscale Gulf Stream eddies are numerous but almost exclusively of cyclonic eddies. Although isolated observations of anticyclonic eddies date back over 30 years to Iselin (1936), no synoptic studies of these features were undertaken until 1968, as described by Saunders (1971) and Thompson and Gotthardt (1971). Saunders encountered a large anticyclonic Gulf Stream meander south of Cape Cod and observed the subsequent formation of an eddy during a four-month period. Thompson and Gotthardt observed a similar anticyclonic eddy the following year and studied its movement and dissipation for nearly five months.

Cyclonic eddies have received considerably more coordinated attention than their anticyclonic counterparts. Multiple ship operations such as "Operation Cabot" and "Gulf Stream 60" recorded by Fuglister and Worthington (1951) and Fuglister (1963) have provided detailed descriptions of cyclonic eddy formation and movement. Five months of observations of two cyclonic eddies during the autumn and winter of 1965 by Fuglister (1971) provided nearly synoptic observations of many aspects of cyclonic eddy life cycle and relationship to surrounding water masses.

This report presents the results of over three years of extensive study of western North Atlantic thermal structure from November 1969 through May 1973. The purpose of the study was to observe the meandering of the Gulf Stream on a continuous basis at sufficiently close intervals to observe the formation of eddies and their subsequent life cycle.

## II. DATA COLLECTION

The data collection was basically a near-synoptic approach, surveying large ocean areas repeatedly during each oceanic season. To accomplish this, a high speed, long-endurance research aircraft was chosen as the primary survey platform, providing the capability to survey a 3000 kilometer track of ocean during an eight or nine-hour flight. Measurements made from the aircraft included continuous sea surface temperatures recorded by airborne infrared radiation thermometer (ART) and subsurface thermal structure to 300 meters using aircraft expendable bathythermographs (AXBT). Whenever available, supplementary data from shipboard expendable bathythermograph (SXBT) and salinity/temperature/depth (STD) systems were used.

The survey pattern consisted of an expanding ladder grid oriented normal to the direction of the Gulf Stream beginning seaward of Cape Hatteras and extending eastward to longitude 65°W. In 1972 the survey area was extended to 60°W. Leg spacings were 40 to 50 kilometers with each leg extending from the southern boundary of the Gulf Stream northward through the Slope Front. One additional flight during each survey was added south of the Gulf Stream between longitudes 65° and 70°W to locate cyclonic eddies which might drift through the area. Whenever an eddy or a large Gulf Stream meander was encountered, a detailed grid was conducted whenever possible at weekly or bi-weekly intervals in an effort to maintain a continuous series of observations describing the life cycle of the feature. During the three years of data collection sixteen Gulf Stream eddies were observed. Seven of these eddies were studied for periods longer than three months, providing much new information on eddy formation movement and dissipation.

## III. SURVEY RESULTS

Results of 60 surveys are presented in tabular form for cyclonic (Table I) and anticyclonic (Table II) eddies. The three-part code designating (1) eddy type, (2) year observed, and (3) order within the year, will be used to identify eddies throughout the remainder of the report.

### 1. Cyclonic eddies

Nine cyclonic eddies were documented during the study period. As indicated in Table I formation was observed during spring of 1970 and 1971 (C-70-1 and C-71-2) and in autumn of 1972 (C-72-3). Eddy C-72-3

was observed from formation through recontact with the Gulf Stream. The only other cyclonic eddy observed to have possibly coalesced with the Gulf Stream was eddy C-71-1. The remaining five eddies were encountered already separated from the Gulf Stream adrift within Sargasso Water.

Eddy diameters were larger towards the east as Gulf Stream meanders increased in wavelength downstream. Initial diameter of C-70-1 was 90 kilometers, less than half that of C-72-3 which formed nearly 800 kilometers to the east.

After separation from the Gulf Stream, temperatures at 300 meters increased steadily (although slowly, < 0.1°C per day) as the eddies drifted about Sargasso Water. Eddies which rejoin the Gulf Stream show a decrease in 300 meter temperature probably due to an influx of colder Slope Water as the eddy and Gulf Stream reunite.

Temperatures as low as 7.8°C were observed at 300 meters in meanders formed during spring; three degrees lower than those formed during early November when temperatures in surface layers are fairly warm. Such a seasonal effect indicates sinking of surface waters during eddy formation. This was apparent during formation of eddies C-71-2 and C-72-3 as the 17°C isotherm subsided by roughly 2 meters per day before separation from the Gulf Stream. This follows Newton's (1961) observations that cyclonic eddy formation involves sinking and spreading of colder Shelf and Slope Waters similar to the sinking and spreading of cold air in developing atmospheric cut-off lows.

All cyclonic eddies observed extended vertically well below the depth limits of the AXBT (300 meters) and SXBT (750 meters). Deep STD casts taken in the core of C-72-3 documented the eddy's extent to at least 2500 meters.

a. Eddy Formation

Figures 1A through 1D show the development of eddy C-70-1 during May and June 1970. Initial northward displacement of the Gulf Stream (Figure 1A) along 74°W intensified as a large anticyclonic meander moved eastward (Figure 1B) converging with a strong Slope Front along the leading edge of the meander. By 20-21 May the Gulf Stream crossed 38°N at 72° 30'W, nearly 100 kilometers north of the historical mean position for this period (Gulf Stream Bulletin, June 1970). Entrainment of colder (< 20°C) Slope Water (Figure 1C) occurred as the meander moved eastward. Seven days later (Figure 1D) the Gulf Stream returned to a more direct path isolating a cyclonic eddy 90 kilometers south of the previous position on 1 June. A bathythermograph section taken by RMS FRANCONIA (Figure 2) through A-B of Figure 1D shows the vertical structure of the eddy extending to the 750 meter limit of the instruments. At the surface a shallow outer ring of Gulf Stream Water, as described by Parker (1971), surrounds the eddy. The area of cold water at the surface is roughly 20 percent of the eddy area at 300 meters.

With minor exceptions formation of all three cyclonic eddies was similar and closely paralleled the stages of development outlined by Fuglister (1971). In each case the Gulf Stream formed a deep trough or cyclonic meander which pinched off at the neck isolating an elliptical mass of Slope Water surrounded by an outer ring formed by the Gulf Stream.

Formation of C-71-2 followed this pattern closely. During late April and early May the Gulf Stream was 60 kilometers north of its mean position in the area west of eddy formation (Gulf Stream Bulletin, May 1971). The eddy separated from the Gulf Stream between 25 May and 8 June moving nearly due east at 11 cm $sec^{-1}$. This initial eastward movement (all others observed moved initially to the south) may have been influenced by contact with eddy C-71-1 sometime between 10 and 25 May. Figure 3 shows the path of eddy C-71-1 moving westward along a spiraling path, while the large cyclonic meander approached from the northwest. Perhaps eddy C-71-1 was reabsorbed by the meander which then formed a second cyclonic eddy (C-71-2) or it was deflected away from the meander out of the survey area. The extremely large diameter of the new eddy (160 kilometers) presents a strong case for reabsorption. Earlier interpretation (Gulf Stream Bulletin, May 1971) that the 10 May observation was a new eddy forming seems unlikely in view of the formation of another eddy within fifteen days at the same location.

The third eddy formation observed occurred in November 1972. The eddy, C-72-3, was the largest and farthest east of any observed during the entire survey period. Thermal structure at the surface and 200 meters east of Cape Hatteras from 31 October to 3 November is shown in Figures 4A and 4B. Along 60°W the Gulf Stream extends southward in deep cyclonic meander. Minimum surface temperature within the meander trough (20-21°C) is equivalent to Slope Water temperatures 200 kilometers to the north. The small area of cold water at the surface where separation from the Gulf Stream has occurred is similar to eddy C-70-1. At 300 meters thermal features are more clearly defined. The area west of 68°W contains two anticyclonic eddies (discussed in section 2). The Gulf Stream maintains an 0.2 to 0.3°C per kilometer gradient from Cape Hatteras eastward to the meander region. The much larger extent of cold water (< 17°C) at this level is apparent extending southward to near 38°N. A survey of the area five days later (Figures 5A and 5B) revealed the Gulf Stream's return to a path above latitude 40°N isolating the slightly elliptical 200 kilometer eddy. Initial movement of the eddy was rapid and to the south-southwest nearly 150 kilometers in five days. At the surface the 23° isotherm outlines the eddy. A mass of 24°C water partially surrounding the eddy is apparently a remnant of the outer "ring" formed by the Gulf Stream. Such an early destruction indicates this outer ring to be a transient structure compared to the observed life time of the inner core of cold water.

b. <u>Movement and Dissipation</u>

Analytical results of Warren (1967) and the barotropic modeling of Pickett (1971) both agree to an overall westward drift of cyclonic

eddies related to Coriolis acceleration. Pickett includes an additional northward component of drift due to inertial and Coriolis accelerations while Warren's conclusions point to a southerly component. Parker's (1971) study of historical data in the western North Atlantic indicates cyclonic eddies either translate directly westward describing anticyclonic loops, or southwestward away from the Gulf Stream.

The three eddies observed during formation all decreased in drift rate after an initially high rate during separation (11 to 50 cm $sec^{-1}$). Eddies observed three times or more showed a tendency toward a looping, anticyclonic trajectory (except eddy C-70-2, the most western eddy observed, which moved more directly to the southwest). This type of movement resulted in recontact with the Gulf Stream by eddies C-71-1 (Figure 3) and C-72-3. Figure 6 shows the movement of eddy C-72-3. Between formation time and mid-December the eddy maintained a nearly south-southwestward course before losing all of its initial impetus. During the next two months the eddy drifted westward between 1 and 2 kilometers per day. As the eddy progressed westward a large cyclonic Gulf Stream meander moved eastward until the meander trough was less than 60 kilometers from the eddy (Figure 7) at the 300 meter level. Interaction between eddy and Gulf Stream at this point is apparent as a sudden collapse of the eddy occurred between observations on 5 and 13 February. Measurements of the subsidence rate of the 17°C isotherm between 8 November and 5 February indicated a fairly constant rate of slightly less than 1 meter per day. Between 5 and 13 February this rate increased to over 3 meters per day. An STD section taken through the eddy in January prior to recontact with the Gulf Stream showed a strong cyclonic circulation up to 100 cm $sec^{-1}$ concentrated primarily above 200 meters in a high velocity ring roughly one half the diameter of the eddy (Khedouri and Gemmill 1973).

The three eddies observed west of 68°W (C-70-1, C-70-2, and C-71-4) apparently followed a more direct course southwestward away from the survey area. Richardson, Strong, and Knauss (1973) presented convincing evidence that eddy C-70-2, after losing its initial impulse from the Gulf Stream during separation, drifted slowly southwestward to probable reabsorption by the Gulf Stream off the northeast coast of Florida nearly two years after formation.

Eddy C-71-3, the southernmost eddy observed, also drifted southwestward, away from the Gulf Stream. Temperature minimum of 14°C at 300 meters and 160 meter depth of the 17°C isotherm follow Parker's (1971) observations that southward moving eddies sink, gradually losing identity in the surface layers. Bathythermographs taken in the core of this eddy showed no evidence of the eddy above 100 meters.

2. Anticyclonic Eddies

Seven anticyclonic eddies were documented during the study period. As indicated in Table II each eddy was observed for at least three months with the longest surveillance being eight months.

Eddy diameters increased with eastward location. The two eddies observed during formation (A-72-2 and A-73-2) were extremely large in diameter (> 250 km) and highly elliptical when newly separated from the Gulf Stream. Within a short period, however, both eddies were modified considerably.

Young eddies were characterized by temperatures greater than 18°C at 200 meters. Temperatures at this level cooled very slowly (≈ 0.01°C per day) throughout the eddy life cycles. Temperatures as high as 16.6°C were recorded at 200 meters in eddy A-72-1, eight months after separation from the Gulf Stream.

a. Eddy Formation

Two anticyclonic eddies (A-72-2 and A-73-1) formed within a six month period at nearly the same location.

Formation of eddy A-72-2 occurred during August 1972. Figures 8A and 8B show the surface and 200 meter thermal structure of the area west of Cape Hatteras 2 to 10 August. At the surface the 27°C isotherm outlines the Gulf Stream northern edge from Hatteras through a large "S" shaped meander over 700 kilometers in wavelength. Across the northern boundary of the meander convergence of cooler Shelf Water forms a seaward extension of the Slope Front roughly 0.2°C $km^{-1}$. At 200 meters a gradient of 0.2°C $km^{-1}$ marks the Gulf Stream northern boundary. The convoluted path of the Stream is apparent as the meander is nearly folded over against itself extending Gulf Stream Water to 40°N. The distance across the neck of the meander is less than 100 kilometers. An older anticyclonic eddy (A-72-1) first observed during March 1972 is apparent less than 90 kilometers to the west of the meander. Survey of the meander area 12 to 16 August (Figures 9A and 9B) indicated the Gulf Stream had returned to a more direct path across the meander neck isolating an anticyclonic eddy. At the surface this is somewhat evident from the 26°C isotherm although the most prominent feature remains the Slope Front extending for 200 kilometers along latitude 40°N. At 200 meters the 15°C isotherm outlines the newly separated eddy some 50 kilometers west of the Gulf Stream. The eddy is elliptical with long to short axis ratio of more than 2 to 1. The area encompassed by the 15°C isotherm at 200 meters is approximately $2 \times 10^4$ $kilometers^2$. A bathythermograph section (Figure 10) taken across points B-B of Figure 9A shows the structure of the eddy rapidly decreasing in horizontal area with depth. The slope of isotherms indicates separation occurred initially in deeper layers.

Elongation of Gulf Stream meanders observed during anticyclonic eddy formation is the result of convergence of the Gulf Stream and Slope fronts. Similarities observed in the formative stages of anticyclonic eddies are shown schematically in Figure 11. Initial northward displacement of a large anticyclonic meander is deflected westward by the Slope

Front. The meander deepens to the west surrounding an elliptical mass of Sargasso Water. Eventual separation occurs as the Gulf Stream closes off the neck of the meander returning to a more direct path.

Formation of eddy A-73-2 followed this pattern closely. Survey of the Gulf Stream area on 12 and 13 February (Figure 12A) shows a seasonally strong Gulf Stream from (0.3 to 0.4°C per kilometer) at the surface. East of 66°W the Stream enters a large anticyclonic meander roughly the same wavelength as the August 1972 meander. The most intense gradient (0.5°C per kilometer) once again is along the northern meander boundary as Shelf and Gulf Stream waters converge. A secondary meander at the easternmost boundary of the survey area appears at 200 meters (Figure 12B) to be already separated from the Gulf Stream. Also of interest, centered near 73°W, eddy A-72-2 is near recapture by the Gulf Stream. A survey of the area east of 69°W two weeks later, 1-2 March, (Figure 13A) revealed the recent separation of the eddy. The eddy boundary is particularly intense along the northwest where temperatures drop from 15°C to 5°C in less than 30 kilometers. The newly separated eddy roughly 20 kilometers from the Gulf Stream, is similar to A-72-2 in size and location.

Immediately to the west another small, circular anticyclonic eddy is present (which was not observed during the first survey). At 200 meters (Figure 13B) cooler temperatures within this smaller eddy (15.6°C) indicate a much earlier formation, (the possible relation of this feature to eddy A-72-2 is discussed in a later section).

b. Movement and Dissipation

During November 1970 a bathythermograph section from New York to Bermuda revealed an anticyclonic eddy roughly 100 kilometers in diameter adjacent to the Continental Slope (A-70-1). Subsequent aircraft surveys conducted from November through January tracked the eddy from the original observation on 4 November as it moved along the Continental Slope to eventual recapture by the Gulf Stream northeast of Cape Hatteras. A search for earlier data revealed enough information to give an approximate position for the eddy during early September. Figure 14 shows the movement of the eddy defined by the limits of the 15°C isotherm at 200 meters. Average movement speed increased steadily from 2 kilometers per day east of 71°W to nearly 11 kilometers per day as the eddy approached recapture near 74°W.

Although surface layers were continuously modified by seasonal cooling during the four month, 500 kilometer migration of the eddy, thermal structure at 200 meters remained remarkably conservative. Figure 15 shows bathythermographs taken within the warm core of the eddy. Between August and December temperature at 200 meters dropped only 1.5°C.

During the next three years four more anticyclonic eddies (A-71-1, A-72-1, A-72-2 and A-73-1) were observed to follow the same path toward Gulf Stream recapture. Figure 16 shows a plot of the paths of all five eddies.

An alternative fate of anticyclonic eddies was indicated by the movement of eddy A-71-2 observed first on 29 October 1971 (Figure 17). At the 200 meter level the eddy was completely isolated from the Gulf Stream as indicated by a series of bathythermograph observations taken between the eddy and the Gulf Stream. By 10 November eddy shape became elliptical as a large Gulf Stream meander with amplitude nearly 150 kilometers pushed northeastward and rejoined the eddy to the Gulf Stream proper. A subsequent survey of the area north of the Gulf Stream to the Continental Slope between longitudes 66° and 69°W on 10 December revealed only a small anticyclonic eddy less than 60 kilometers in diameter, roughly 20 percent of the area of the October observation. Apparently the bulk of the eddy was reabsorbed by the Gulf Stream leaving only a small remnant adrift in Slope Water. Although small, this satellite eddy maintained its identity at least through 10 January before becoming lost as survey of the area during February revealed no further information concerning the eddy.

A second indication of early Gulf Stream recapture was apparent from a survey 3 and 4 May 1973. Figure 18 shows the largest meander observed during the survey period. The wavelength of this meander was over 1200 kilometers extending westward from 62°W beyond 68°W. Referring to the formation of the March 1973 anticyclonic eddy (Figures 12 and 13) there seems little doubt that the newly formed eddy extending slightly west of 66°W had by May, two months later, become reabsorbed into a much larger Gulf Stream meander. Situated less than 100 kilometers to the west is the older eddy A-73-1 observed in March. No further information was obtained concerning this meander which quite likely formed a large anticyclonic eddy at some later period.

The likelihood of early recapture of anticyclonic eddies by large Gulf Stream meanders becomes greater the farther east of 70°W eddies form. Documentation of so few anticyclonic eddies in the western Slope Water region suggests that many eddies are formed and recaptured east of this longitude. All anticyclonic eddies observed during the study to reach 68°W without recontact with the Gulf Stream continued westward along the path illustrated in Figure 16.

A graph of average translation rates observed from the seven anticyclonic eddies is presented in Figure 19. Although the numbers are representative of only mean movement between observations they show a marked increase in translation rate westward of 71°W.

An experiment to measure surface current in this area was conducted by Crumpler and Bivins (1972) in September 1970. A satellite tracked drift buoy designed to measure movement in the upper 6 meters was deployed at 71°00'W, roughly in the center of the observed track followed by anticyclonic eddies. The buoy drifted southwestward at an average rate of 10.4 kilometers per day during a 21 day period. The rapid rate of the buoy drift indicates that most of the eddy translation is due to the westward moving mass of water.

As eddies migrate westward a corresponding reduction in size is observed. Comparison of eddy sizes with longitude was made defining size as the area of 15°C water at 200 meters. Since horizontal to vertical ratios in eddies are roughly 100 to 1, changes in horizontal area alone should accurately depict eddy dissipation. A plot of this data is given as Figure 20. The data indicate a linear relationship between dissipation and westward movement. The linear relationship fits all but the earliest observations of the newly formed eddies A-72-2 and A-73-2. Both eddies in early stages of separation from the Gulf Stream were extremely elliptical having similar eccentricities of 0.89 and 0.85 respectively. In addition both eddies apparently underwent additional modification soon after separation from the Gulf Stream.

Survey of eddy A-72-2 two months after formation showed the eddy to be nearly circular and less than 50 percent of initial size. This rapid change appears to be the result of the breakup of the elongated eddy soon after separation from the Gulf Stream. The western portion of the larger eddy translated westward and was observed through February 1973. The eastern portion remained partially entrained within the eastward flow of the Gulf Stream before gradually drifting westward, being relocated on 2 March as the small, older eddy A-73-1. Eddy A-73-2 as described earlier was apparently absorbed by a large Gulf Stream meander within 2 months of formation.

Hydrographic stations through A-70-1 in December, at least three months after separation from the Gulf Stream revealed rotational currents of 120 cm $sec^{-1}$ centered mostly within a high velocity ring (similar to C-72-3) above 200 meters.

## IV. DISCUSSION

The 42 month study indicates that eddies are an integral part of the thermal structure of the western North Atlantic. Considering the actual survey time was only a small portion of the 42 months and that gaps in coverage exist both temporally and spacially, a number of eddies may have remained undiscovered. The chances of discovery certainly increased with the thoroughness of each survey. Thus surveys in August and November of 1973, after two years of perfecting survey techniques, revealed four eddies present within the survey area during the same time period. During these two surveys roughly 10 percent of the area studied was influenced by Gulf Stream eddies.

The number of Gulf Stream eddies formed each year remains an interesting question. Fuglister's (1971) estimate of the formation of 5 to 8 of each eddy type per year cannot be contradicted by this study during which every large meander observed eastward of longitude 70°W formed an eddy. According to Newton (1961) the passage of one meander every 50 days at a point is possible. Assuming each formed an eddy the result would be 7 pairs of Gulf Stream eddies per year.

Observations indicate formation of both cyclonic and anticyclonic eddies to be basically similar. In both cases Gulf Stream meanders steadily increase in amplitude and wavelength surrounding and eventually isolating a large mass of Sargasso or Slope Water.

Relating eddy formation to season is tenuous. The data documents cyclonic eddy formation in late spring and autumn. Fuglister (1951) and (1966) also observed cyclonic eddy formation in June 1950 and October 1965. Anticyclonic eddies were observed to form in August and February. Anticyclonic eddy formation was also observed by Hansen (1970) in March 1966 and 1967 and by Saunders (1971) in October 1969. Rather than season, eddy formation appears more related to the displacement of the Gulf Stream during the initial stages of meander formation. In all observations of Gulf Stream meandering initial displacement north of the mean position resulted in a cyclonic eddy with the opposite being true for anticyclonic eddies. According to Iselin (1940) the Gulf Stream is farthest south during periods of maximum flow and farthest north when flow is weakest. Coincidentally, periods of maximum Gulf Stream flow observed by Montgomery (1938) and Hela (1952) occur in July and January roughly corresponding to the observed times of formation of anticyclonic eddies. (The eddy observed by Saunders being an exception). The periods of minimum flow during April and October when the Stream is farthest north likewise approximate times of observed formation of cyclonic eddies.

Anticyclonic eddies, once isolated from the disruptive influence of the Gulf Stream, establish a stable structure and drift westward decaying at a slow constant rate. Referring to figure 16 regression of longitude to eddy area yields the equation:

$$\text{Area (km}^2) = K - 329 \text{ longitude } (^\circ)$$

where $K = 26197 \frac{\text{km}^2}{(^\circ)}$

assumed valid for longitudes 75°W through 60°W. The equation predicts a decrease in eddy size by 329 kilometers$^2$ per degree of longitude. According to these figures an eddy which is recaptured near Cape Hatteras (≃ 74°W) would have lost 65 percent of its initial size to surrounding Slope Water. This is in sharp contrast to the early recapture of 80 percent of eddy A-71-2 by a Gulf Stream meander near 67°W.

Early recapture by Gulf Stream meanders was observed for both eddy types and perhaps accounts for the fate of a large number of newly formed eddies. A type of loop may exist between longitudes 60°W and 70°W whereby large meanders, as they intensify eastward, form eddies which are then recaptured by a successive meander. The loop is broken as the

eddy reaches longitudes west of 70°W where meander amplitudes are much smaller. From this point all anticyclonic eddies drift westward to recapture near Cape Hatteras, while cyclonic eddies apparently drift southwestward away from the Gulf Stream slowly subsiding into the surrounding Sargasso Water.

## V. SUMMARY

Overall the 42 months of observations documented many aspects of the life cycles of both cyclonic and anticyclonic eddies, some for the first time. Because of the large amount of data, a great deal of detailed analysis of each feature was impossible and would have defeated the intent of the paper, to present all the significant events documented during the survey period. The following list summarizes these events:

1. Eddy formation is basically similar for both types as the Gulf Stream surrounds and isolates a mass of Slope or Sargasso Water.

2. Convergence of Gulf Stream and Slope fronts blocks the northward extent of anticyclonic meanders, and provides an available source of cold water during cyclonic eddy formation.

3. During cyclonic eddy formation sinking of Slope Water occurs and upon separation cyclonic eddies receive a strong southward displacement from the Gulf Stream.

4. Separation from the Gulf Stream occurs first in shallow layers for cyclonic eddies. The opposite is observed for anticyclonic eddies.

5. The dimensions of Gulf Stream meanders and consequently the eddies they form increase towards the east. Cyclonic eddies extend to depths of 2500 meters or more. Anticyclonic eddies are shallower features confined to the upper 1000 meters.

6. Internal circulation in both types of eddies is maintained efficiently. Rotational speeds of 100 and 120 cm $sec^{-1}$ were recorded in eddies separated from the Gulf Stream over 3 months.

7. Anticyclonic eddies which survive early recapture, drift upstream along the Continental Slope increasing in speed west of 71°W. These eddies slowly dissipate at a constant rate until recaptured by the Gulf Stream northeast of Cape Hatteras.

8. Cyclonic eddies drift to the west or southwest once the initial thrust from the Gulf Stream is lost. Eddies observed east of 68°W followed a looping trajectory.

9. Cyclonic eddies observed subsided at a fairly constant rate of approximately 1 meter per day while freely drifting in Sargasso Water. Contact with the Gulf Stream caused a sudden collapse of the eddy structure.

10. The physical properties of eddies change very slowly indicating mixing with the surrounding water mass is not rapid.

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| EDDY | OBSERVATION PERIOD | OBSERVATIONS | DIAMETER OF 17C AT 200 METERS (KM) *1 | MINIMUM TEMP. (C) AT 200 METERS *1 | DEPTH OF 17C *1 | POSITION 1st OBS. | POSITION LAST OBS. | SIGNIFICANT OCCURRENCES |
|---|---|---|---|---|---|---|---|---|
| C-70-1 | 1-9 June 1970 | 2 | 90 | 9.5 | 10 | 3710N 6922W | 3621N 6904W | *1 EDDY FORMATION, completely separated from Gulf Stream 8 June<br>+1 Last observation as Gulf Stream meander 1 June |
| C-70-2 | 26 Sept. - 8Nov. 1970 | 2 | 90 | 11.9 | 100 | 3650N 6930W | 3600N 6935W | All data from SXBT sections, eddy never completely circumnavigated |
| C-71-1 | 19 Mar. - 11 May 1971 | 5 | 130 *2<br>110 +2 | 10.5 *2<br>8.9 +2 | 0<br>0 | 3600N 6600W | 3554N 6700W | *2 First observation 19 March<br>+2 RECONTACT WITH GULF STREAM 11 May |
| C-71-2 | 10 May - 15 Aug. 1971 | 5 | 160 *3<br>110 +3 | 7.9 *3<br>12.7 +3 | 0 *3<br>70 +3 | 3700N 6740W | 3445N 6300W | *3 EDDY FORMATION, completely separated from Gulf Stream 25 May<br>+3 Last observation 15 August |
| C-71-3 | 21 - 30 Aug. 1971 | 2 | 120 | 14.0 | 160 | 3410N 6530W | 3350N 6605W | |
| C-71-4 | 12 - 19 Sept. 1971 | 2 | 117 | 13.1 | 100 | 3645N 6835W | 3530N 6905W | |
| C-72-1 | 2 Aug. - 26 Sept. 1972 | 3 | 98 *4 | 13.9 | 260 *4 | 3445N 6645W | 3525N 6715W | *4 From survey 8 August |
| C-72-2 | 6 Nov. 1972 | 1 | 170 | 11.7 | 114 | 3540N 6410W | - | |
| C-72-3 | 3 Nov. 1972 - 1 Mar. 1973 | 8 | 207 *5<br>171 +5 | 11.6 *5<br>11.4 +5 | 119 *5<br>194 +5 | 3900N 6005W | 3615N 6210W | *5 EDDY FORMATION, completely separated from Gulf Stream 8 November<br>+5 RECONTACT WITH GULF STREAM 25 February |

TABLE I
CYCLONIC EDDIES

| EDDY | OBSERVATION PERIOD | OBSERVATIONS | DIAMETER OF 15C AT 200 METERS (KM) | MAXIMUM TEMP. (C) AT 200 METERS | POSITION 1st OBS. | POSITION LAST OBS. | SIGNIFICANT OCCURRENCES |
|---|---|---|---|---|---|---|---|
| A-70-1 | 1 Sept. 1970 - 7 Jan. 1971 | 7 | *1 120<br>+1 100 | *1 18.3<br>+1 16.7 | 3905N 6930W | 3630N 7330W | *1 First observation 1 Sept.<br>+1 Last observation as eddy 29 Dec.<br>RECAPTURE BY GULF STREAM 4 Jan. |
| A-71-1 | 10 May - 23 Nov. 1971 | 8 | *2 110<br>+2 80 | *2 17.3<br>+2 17.3 | 4005N 6550W | 3627N 7340W | *2 First observation 10 May<br>+2 Last observation as eddy 19 Nov.<br>RECAPTURE BY GULF STREAM 23 Nov. |
| A-71-2 | 29 Oct. 1971 - 10 Jan 1972 | 4 | *3 130<br>+3 70 | *3 18.6<br>+3 15.7 | 3900N 6610W | 3930N 6313W | *3 First observation 29 Oct.<br>+3 Last observation 10 Jan.<br>after bulk of eddy RECAPTURED BY GULF STREAM MEANDER 10 Nov. |
| A-72-1 | 13 Mar. - 16 Nov. 1972 | 5 | *4 166<br>+4 103 | *4 18.1<br>+4 16.6 | 4010N 6450W | 3750N 7325W | *4 First observation 13 March<br>+4 Last observation as eddy 16 Nov.<br>EDDY NEAR GULF STREAM RECAPTURE |
| A-72-2 | 10 Aug. 1972- 12 Feb. 1973 | 6 | *5 260<br>+5 94 | *5 18.2<br>+5 15.6 | 4030N 6430W | 3905N 7251W | *5 EDDY FORMATION 16 Aug.<br>+5 Last observation as eddy 12 Feb.<br>EDDY NEAR GULF STREAM RECAPTURE |
| A-73-1 | 2 Mar. - 17 July 1973 | 5 | *6 125<br>+6 120 | *6 15.6<br>+6 16.1 | 3920N 6736W | 3755N 7240W | *6 First observation 2 March<br>+6 RECAPTURE BY GULF STREAM MEANDER 17 July |
| A-73-2 | 13 Feb. - 4 May 1973 | 3 | *7 300 | *7 18.3 | 3950N 6345W | 4010N 6430W | *7 EDDY FORMATION 2 March |

TABLE II
ANTICYCLONIC EDDIES

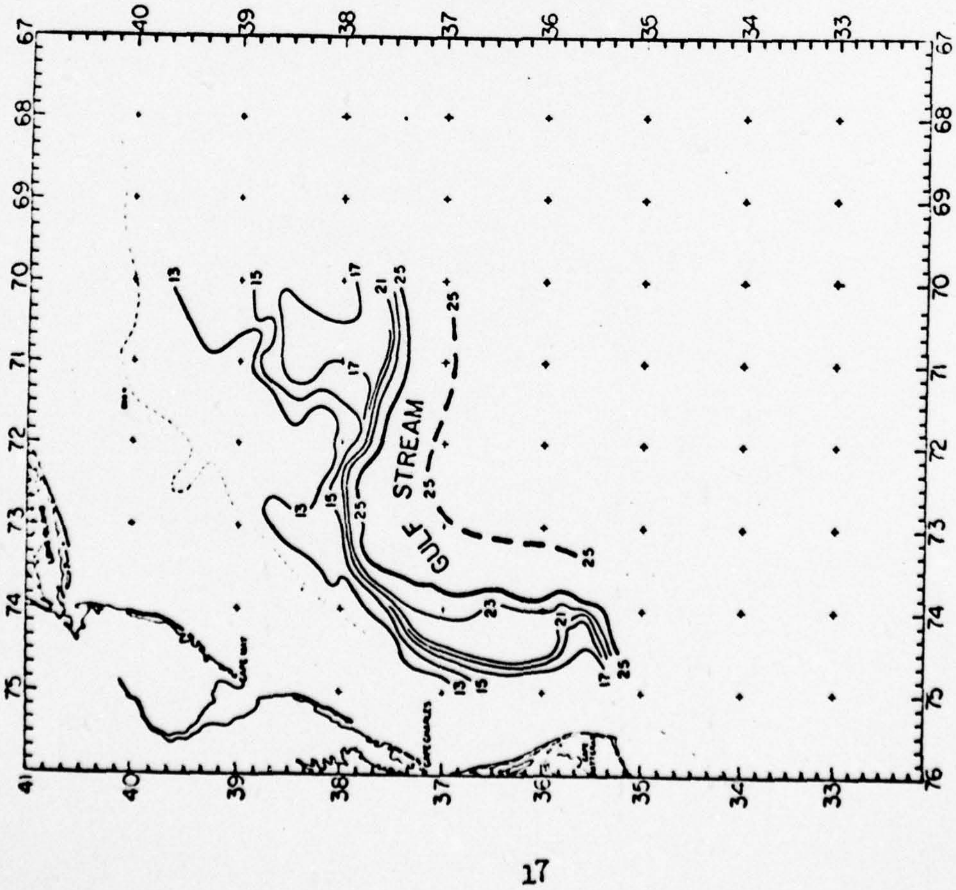


FIGURE 1a. SEA SURFACE TEMPERATURE ANALYSIS (°C)
10-11 MAY 1970

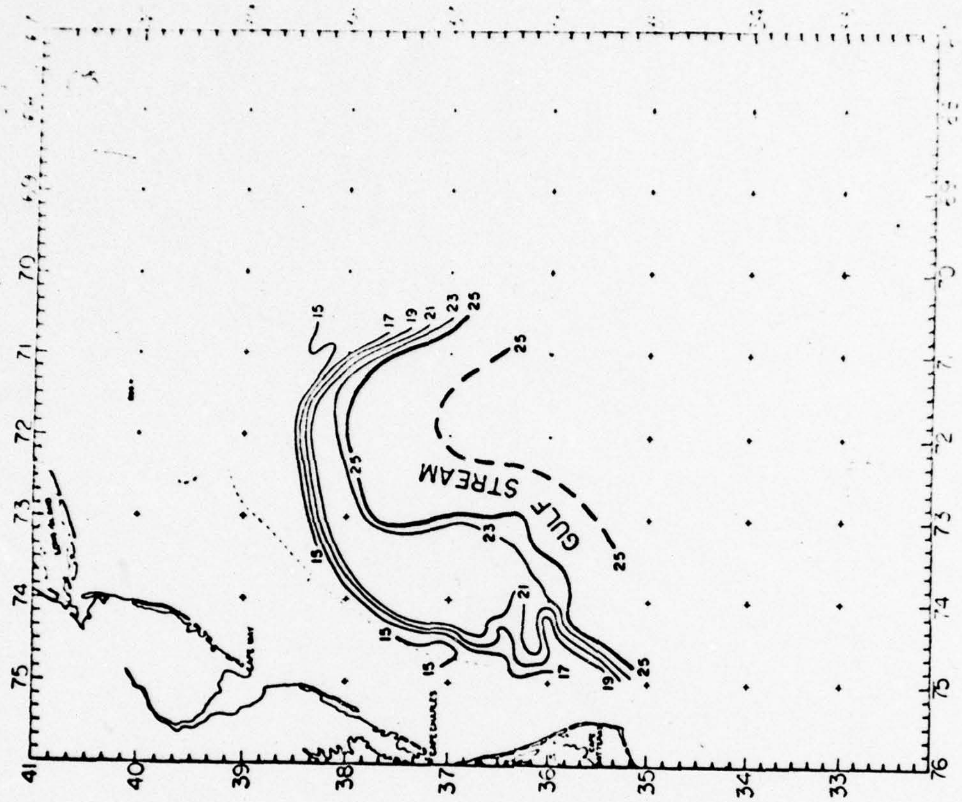


FIGURE 1b. SEA SURFACE TEMPERATURE ANALYSIS (°C)
20-21 MAY 1970

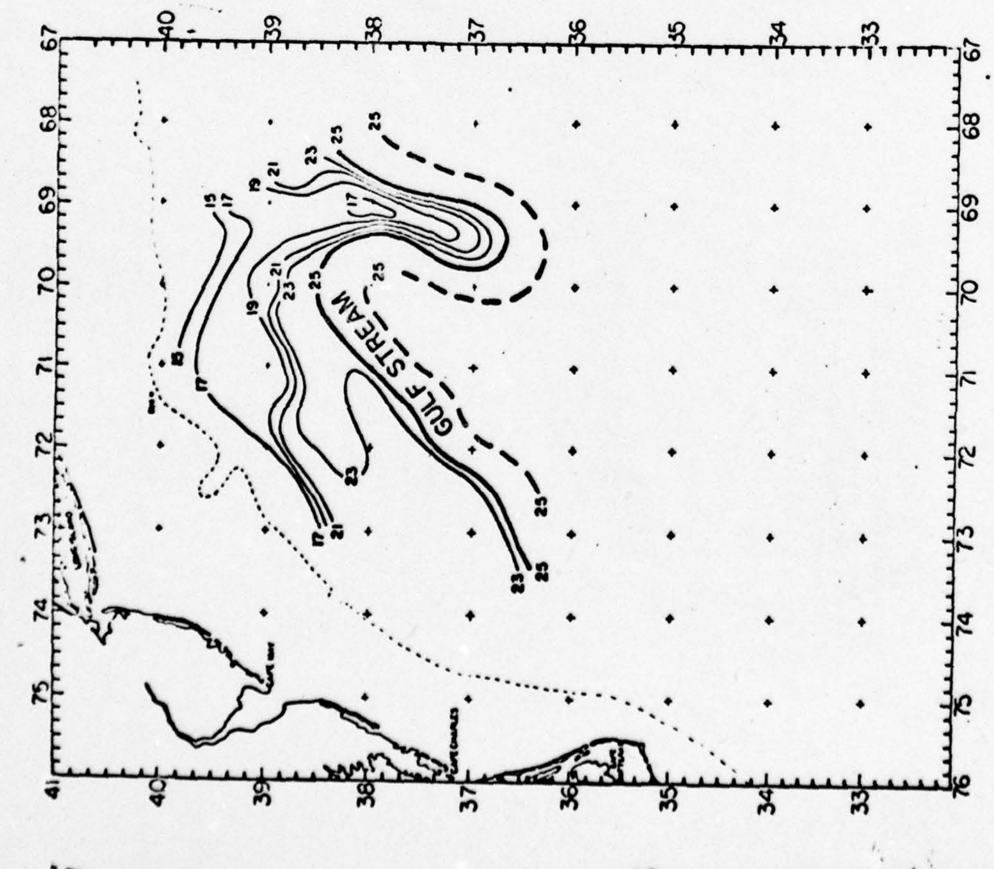


FIGURE 1c. SEA SURFACE TEMPERATURE ANALYSIS (°C)
1 JUNE 1970

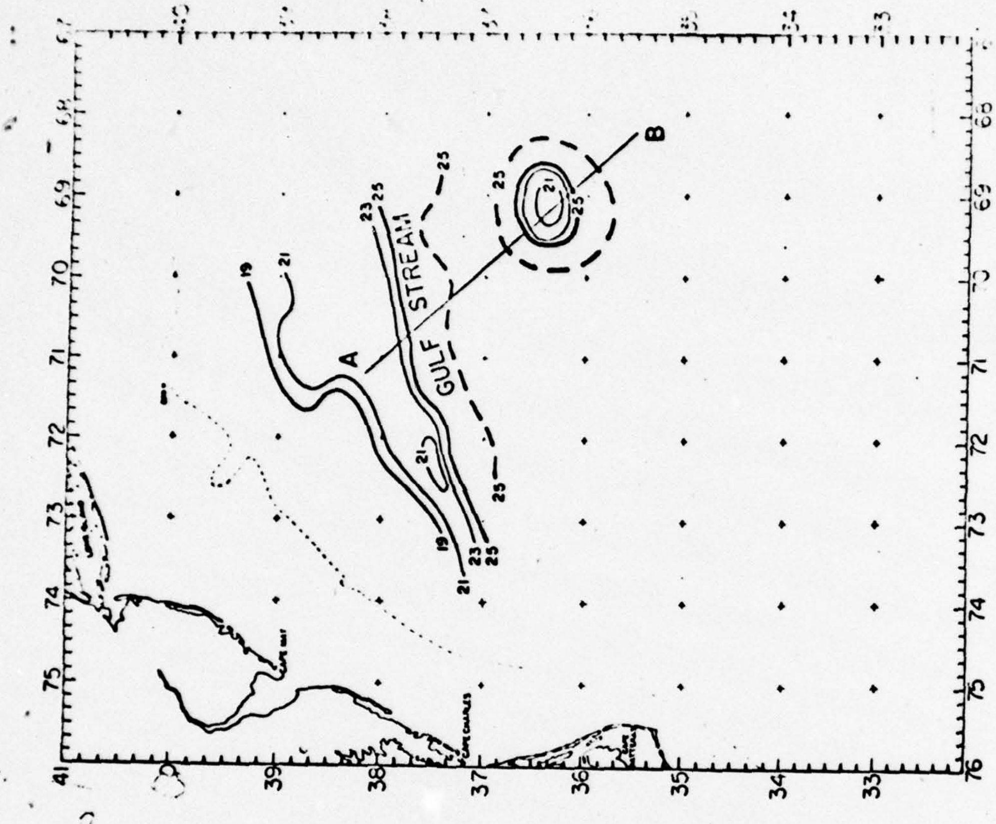


FIGURE 1d. SEA SURFACE TEMPERATURE ANALYSIS (°C)
8 JUNE 1970

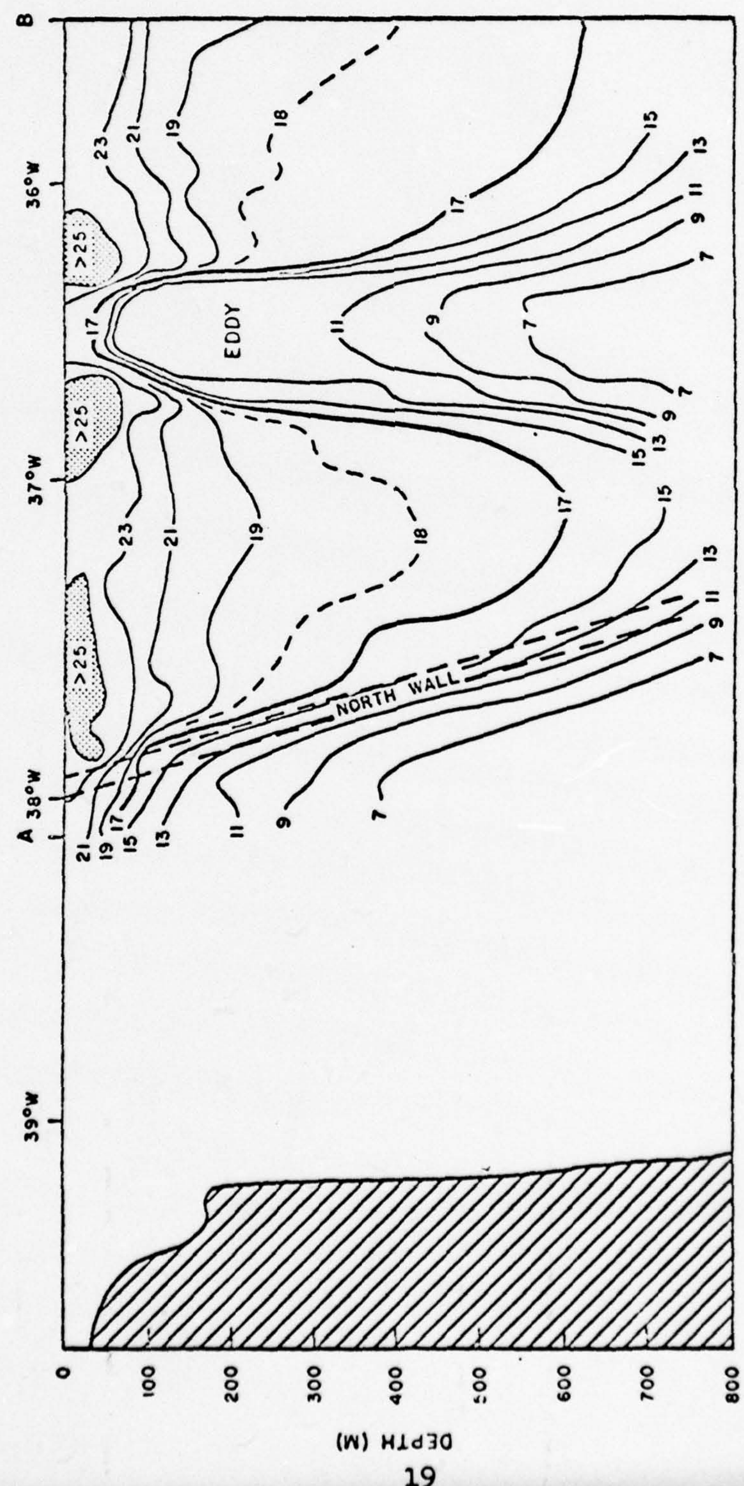


FIGURE 2. BATHYTHERMOGRAPH SECTION (°C) 7–8 JUNE 1970

DEPTH (M)

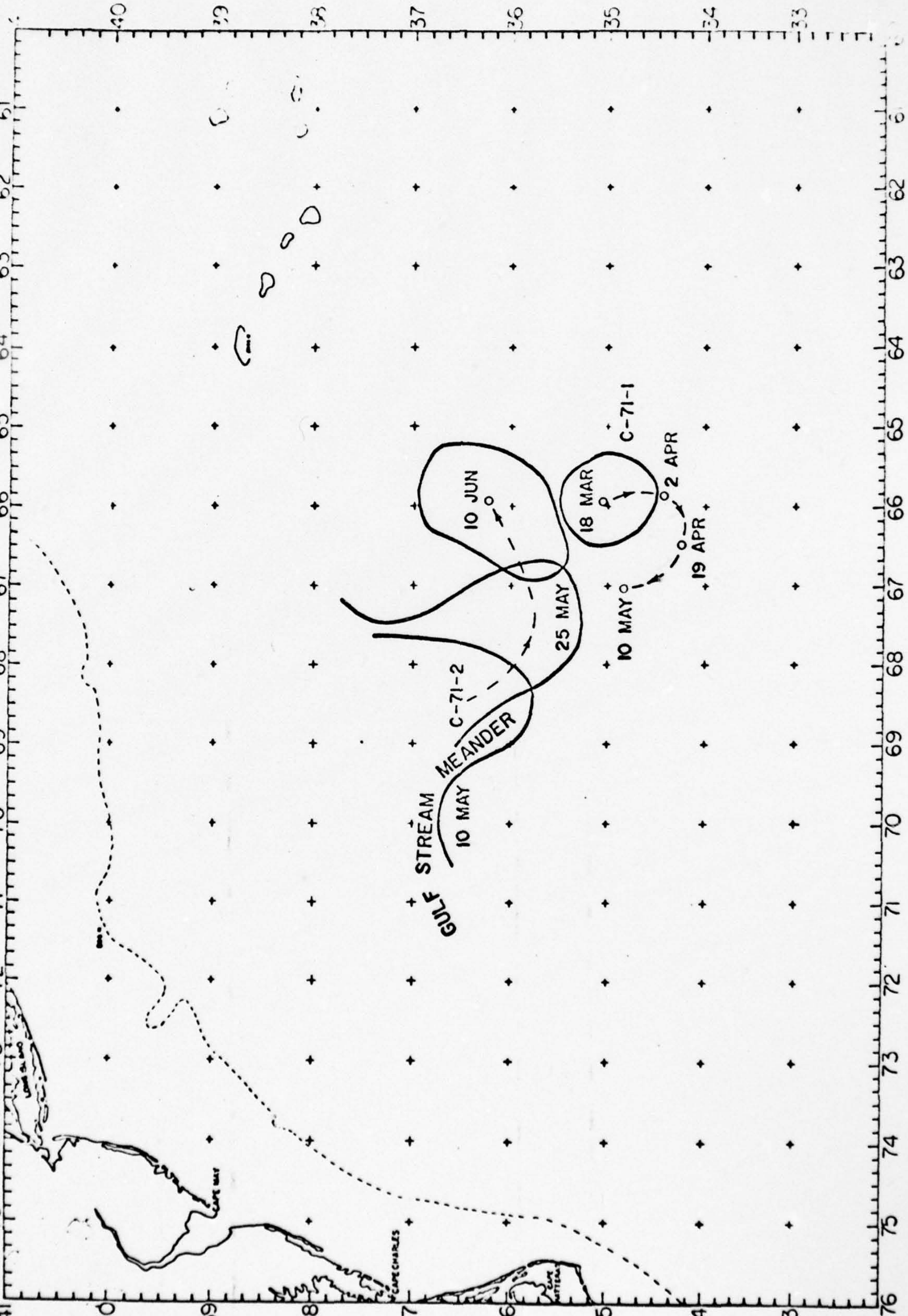


FIGURE 3. MOVEMENT OF C-71-1 AND FORMATION OF C-71-2 18 MARCH–10 JUNE 1971 (17°C AT 300 M)

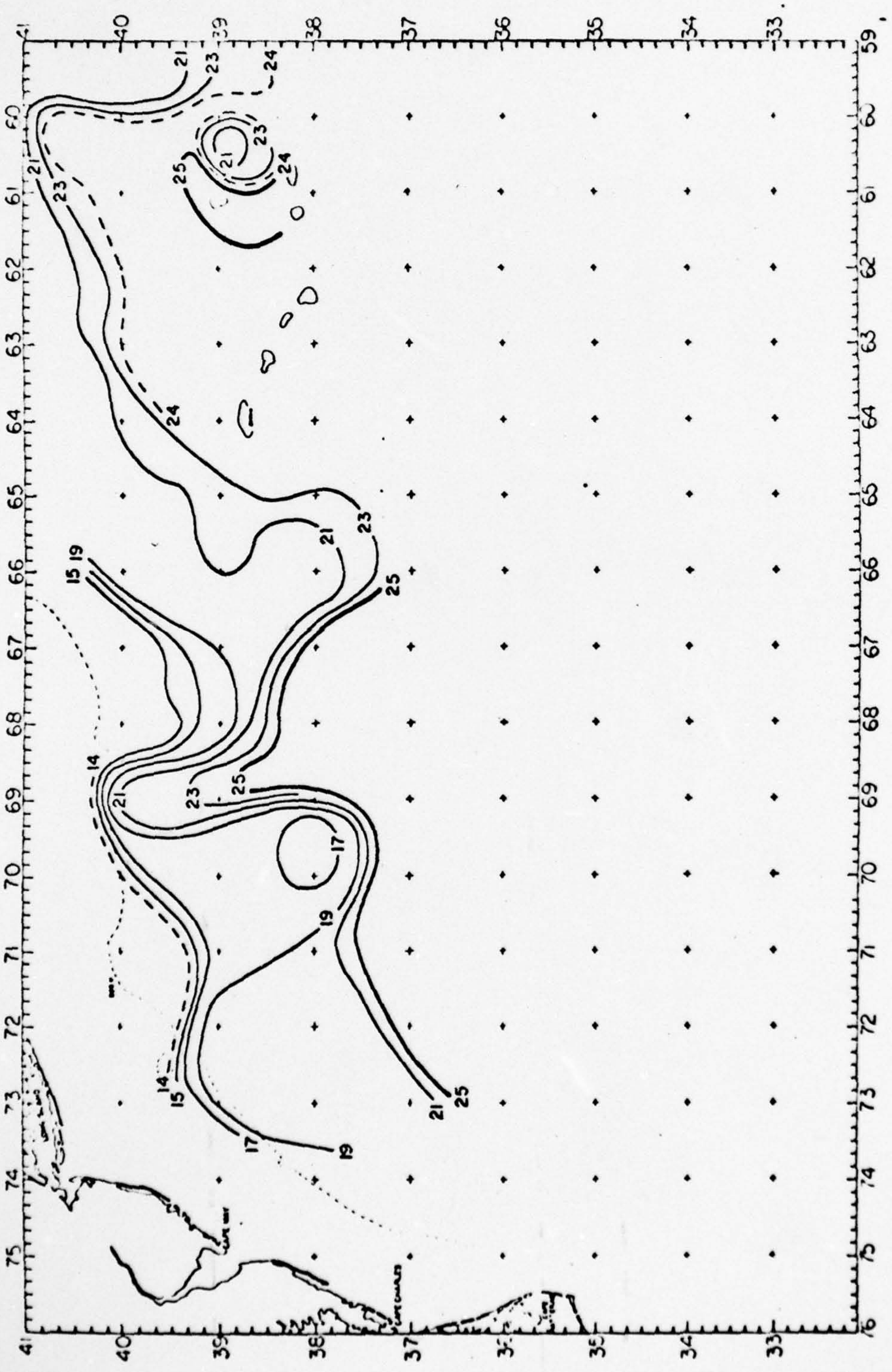

FIGURE 4a. SEA SURFACE TEMPERATURE ANALYSIS (°C) 31 OCTOBER - 3 NOVEMBER 1972

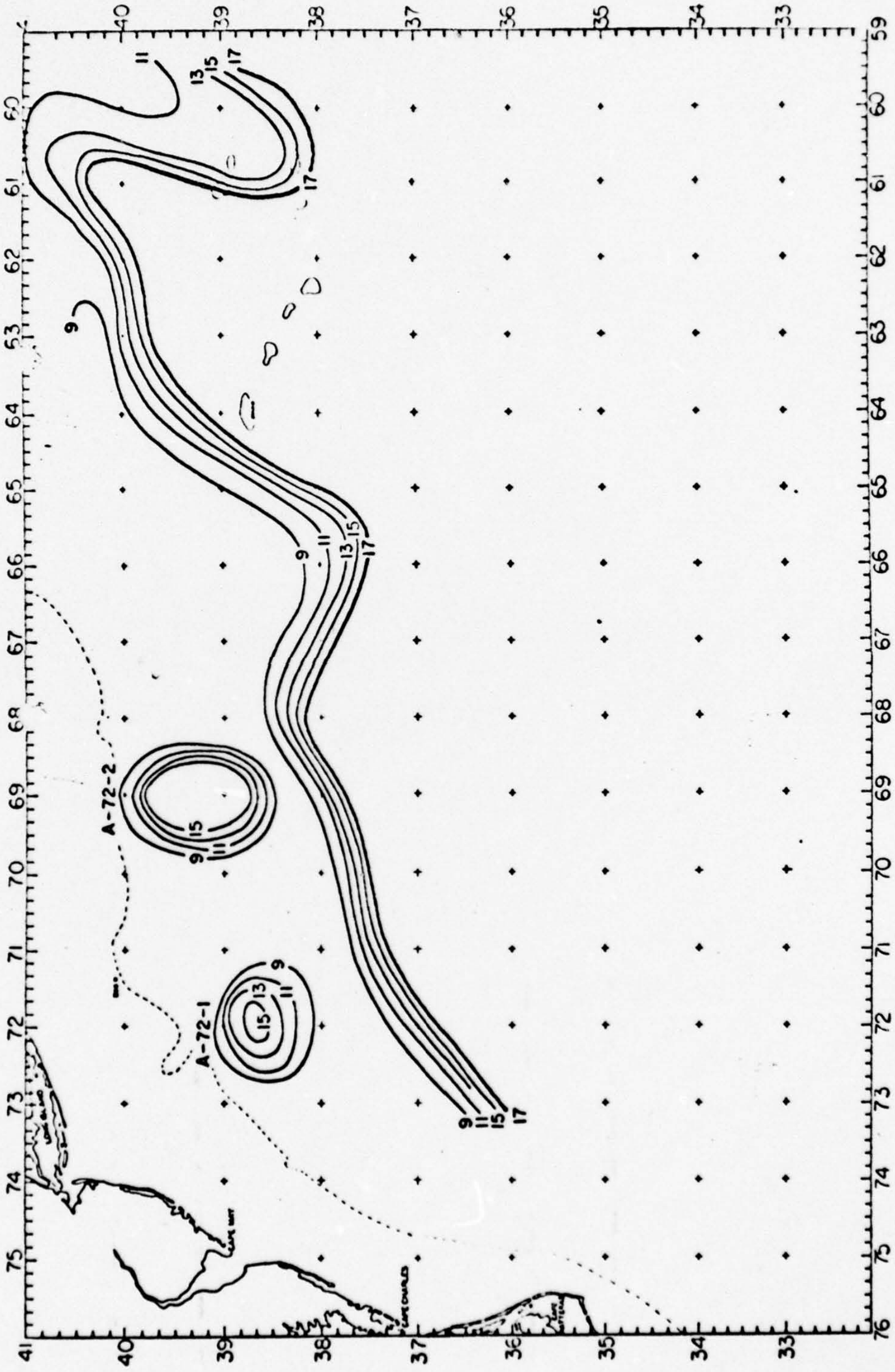


FIGURE 4b. 300 METER TEMPERATURE ANALYSIS (°C) 31 OCTOBER - 3 NOVEMBER 1972

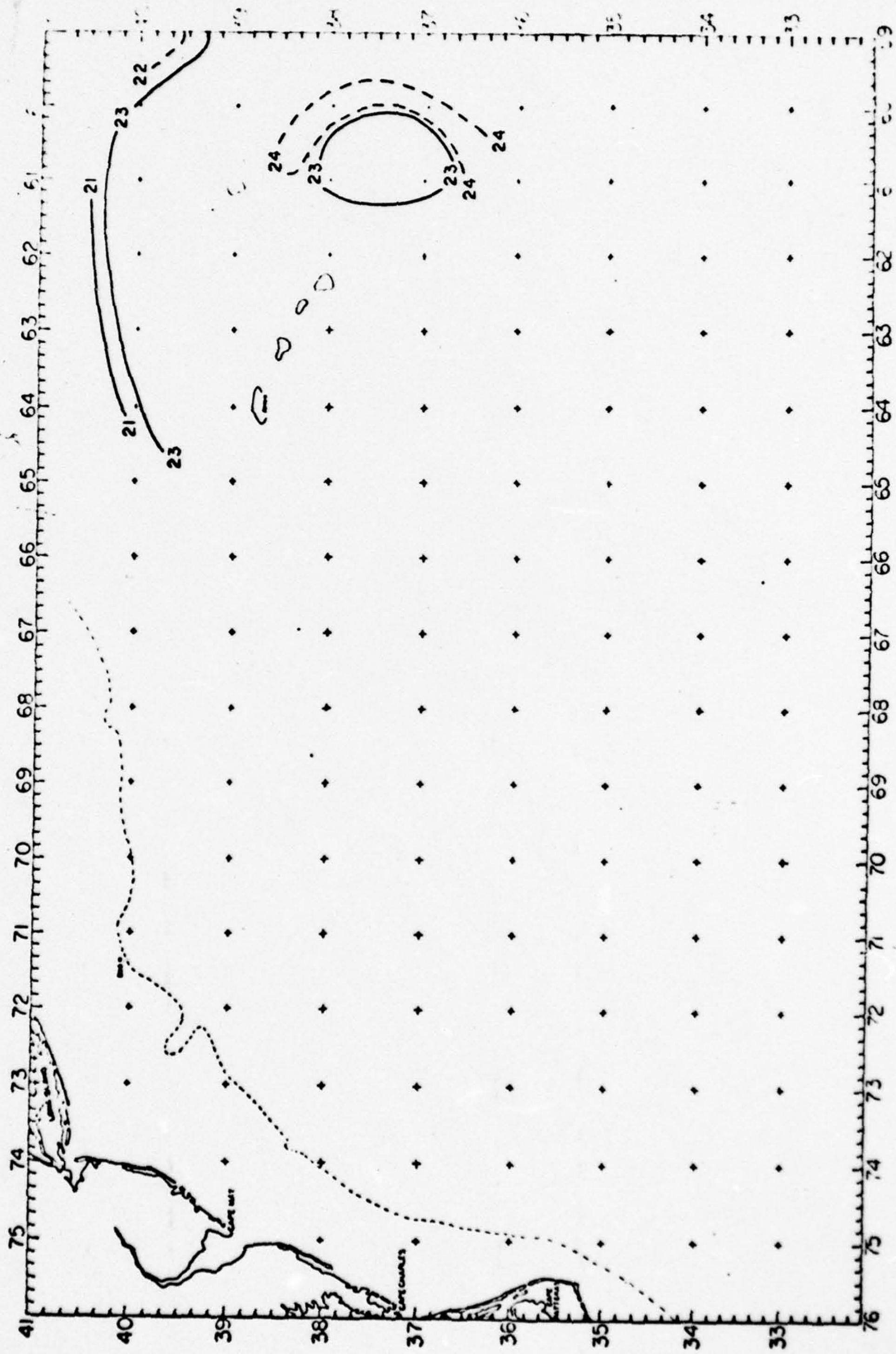


FIGURE 5a. SEA SURFACE TEMPERATURE ANALYSIS (°C) 8 NOVEMBER 1972

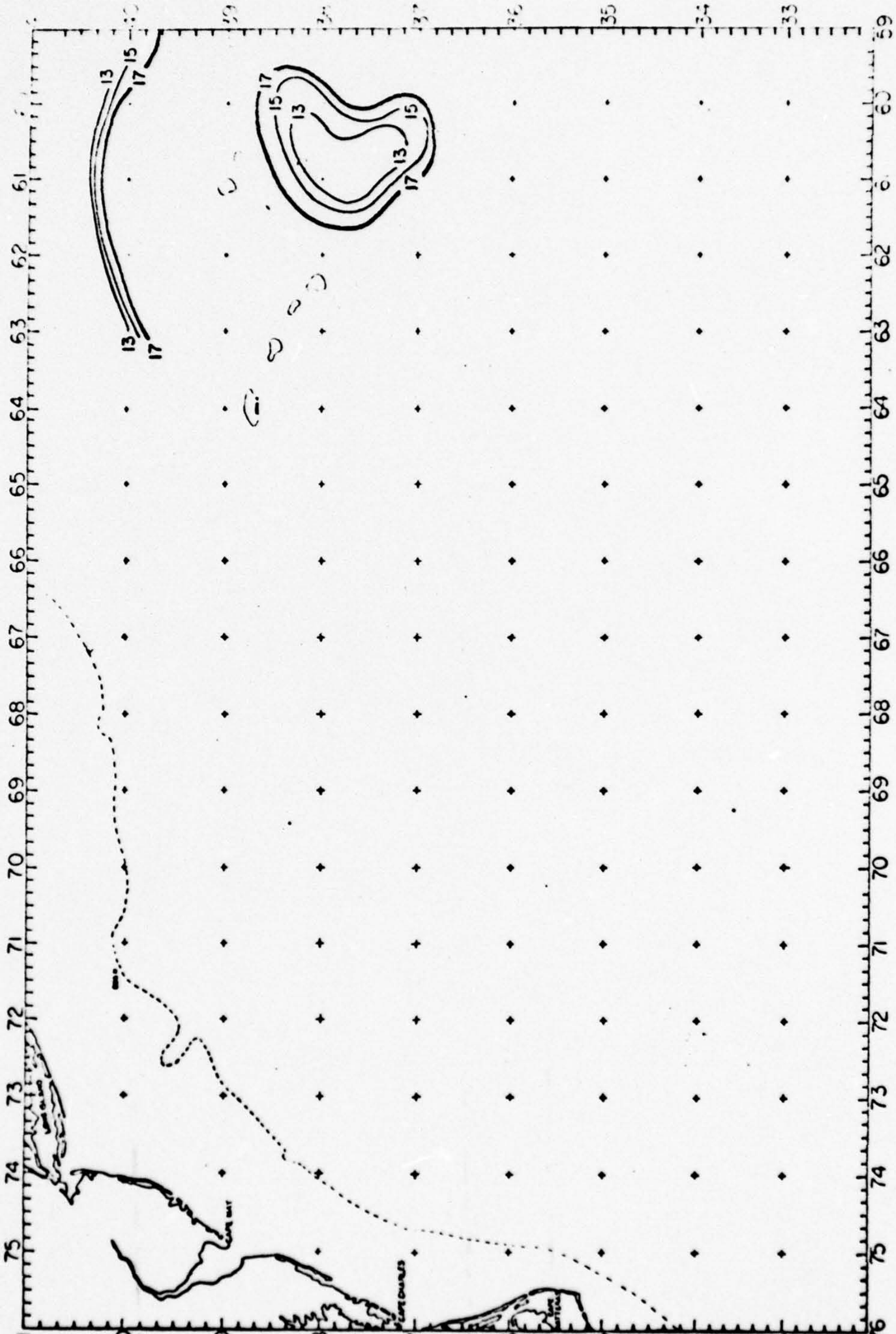


FIGURE 5b. 300 METER TEMPERATURE ANALYSIS (°C) 8 NOVEMBER 1972

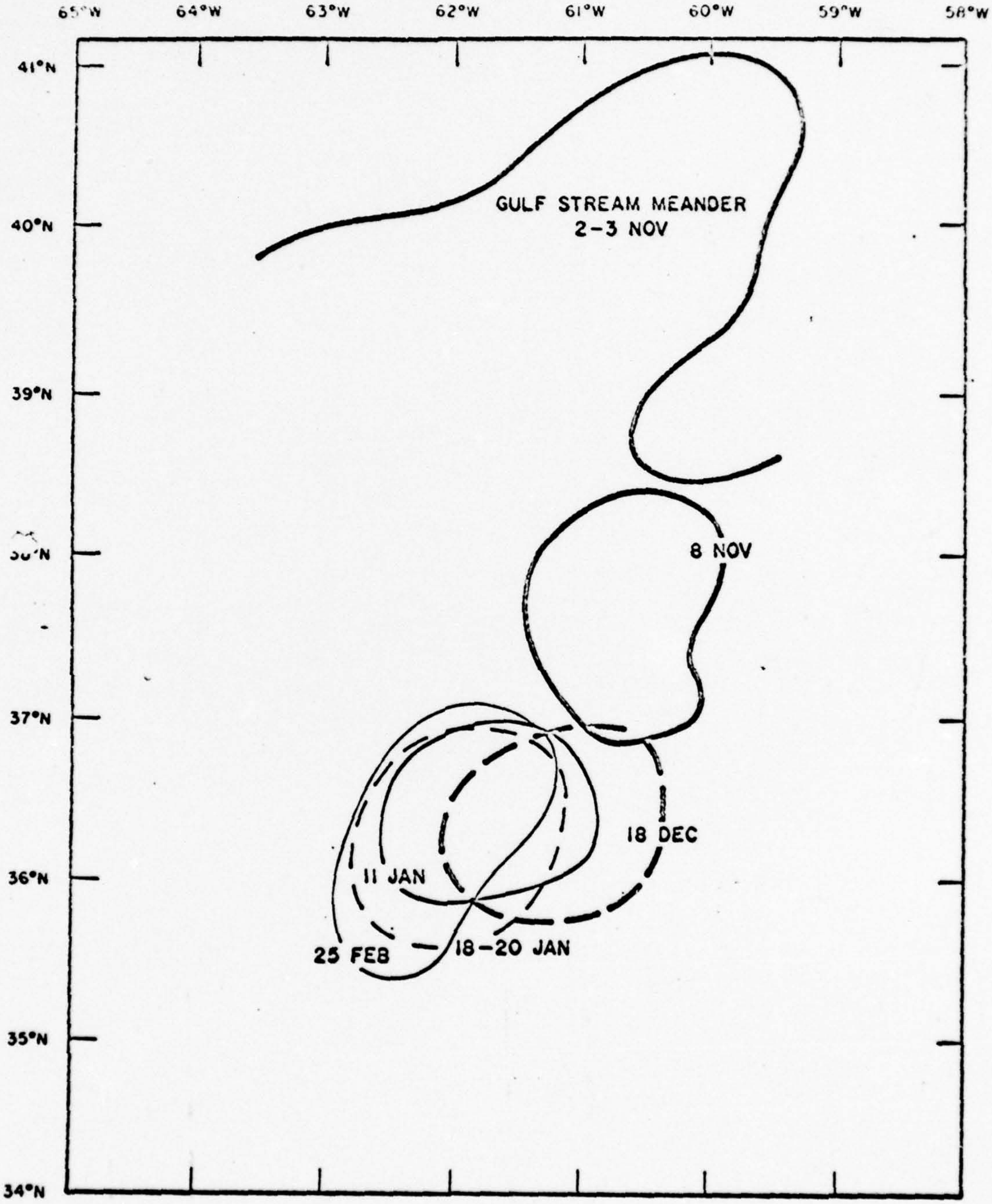


FIGURE 6. MOVEMENT OF C-72-3 2 NOVEMBER 1972-25 FEBRUARY 1973
(17°C ISOTHERM AT 300 M)

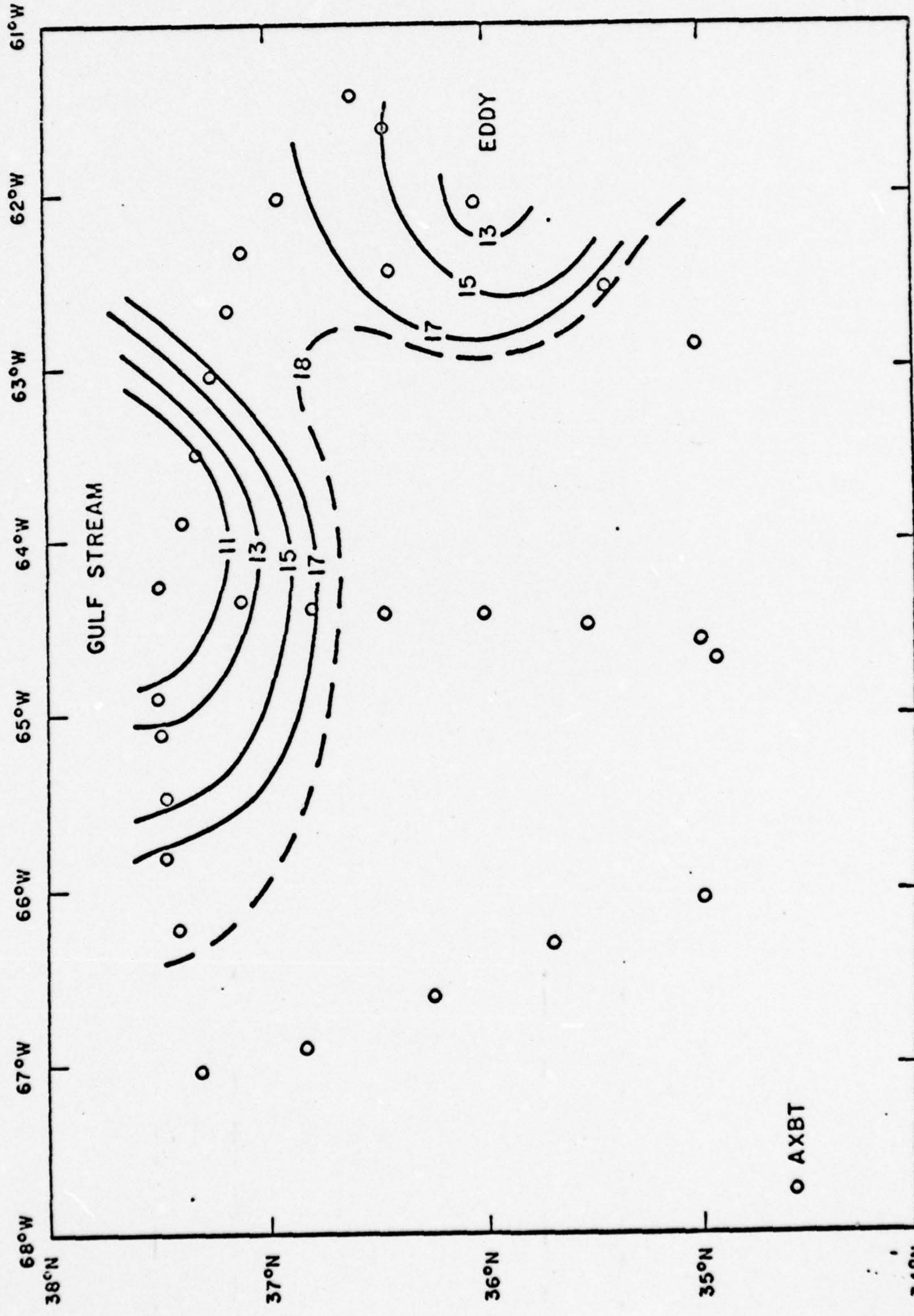


FIGURE 7. 300 METER TEMPERATURE ANALYSIS (°C) 1 MARCH 1973

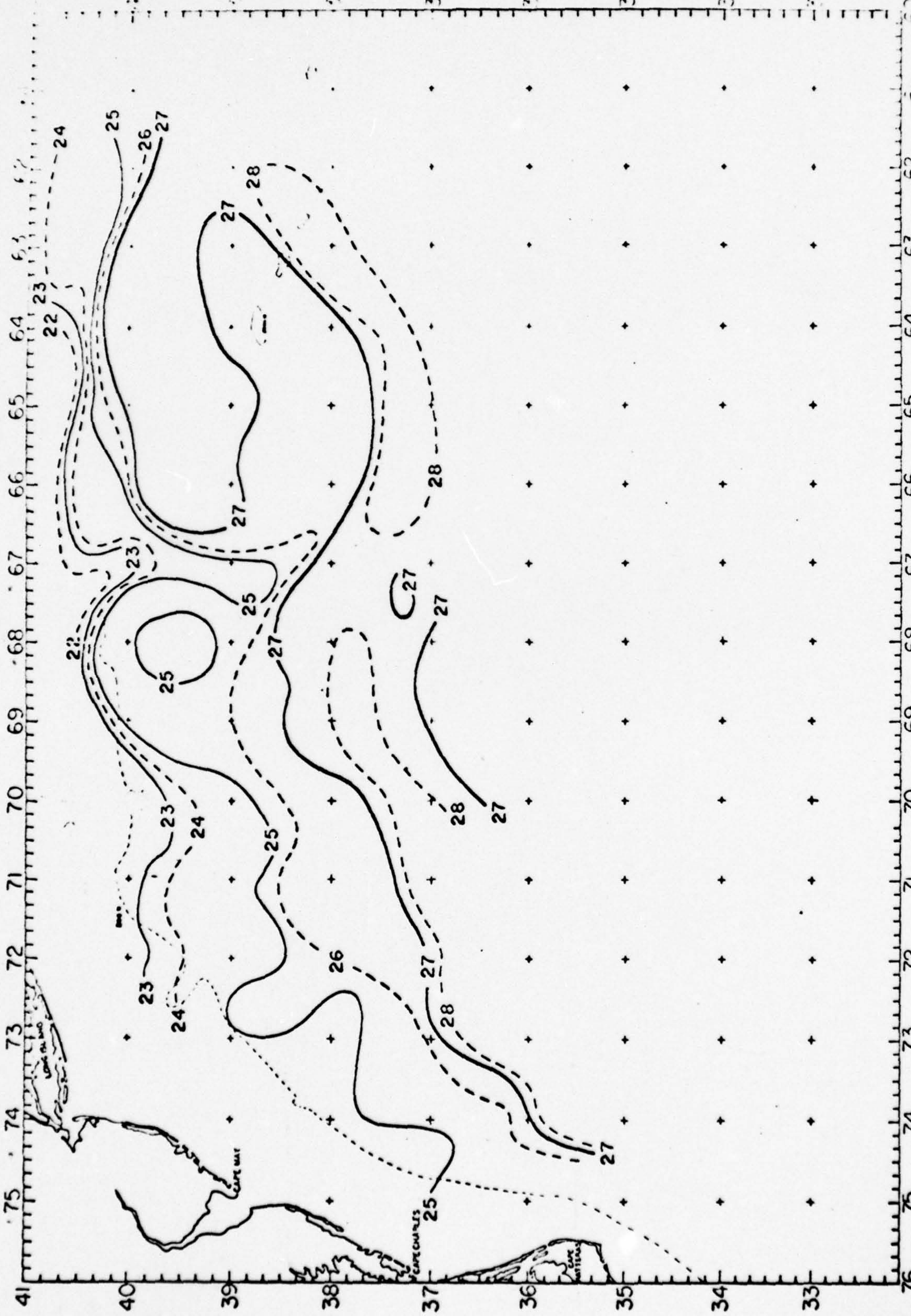

FIGURE 8a. SEA SURFACE TEMPERATURE ANALYSIS (°C) 2-10 AUGUST 1972

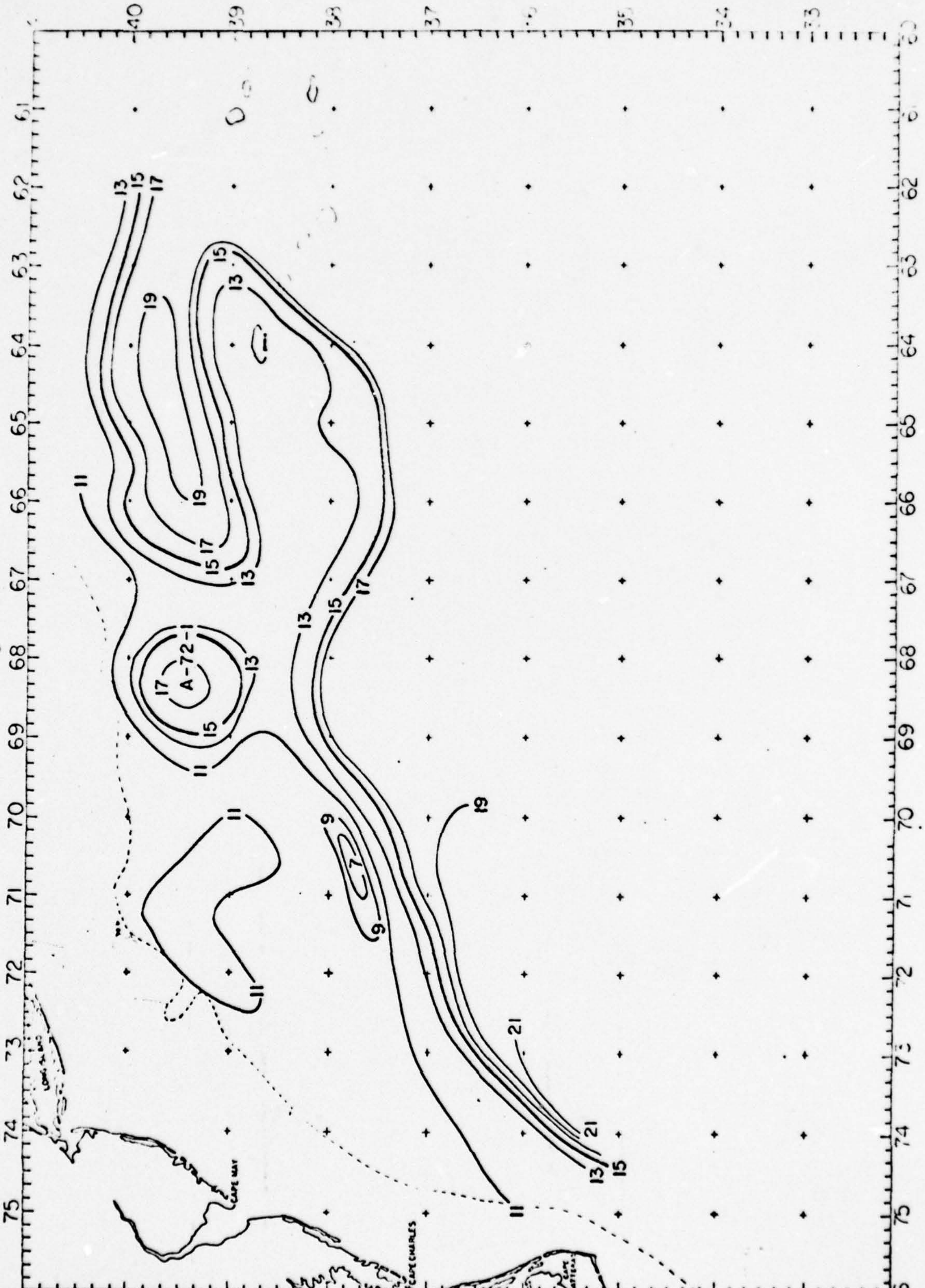


FIGURE 8b. 200 METER TEMPERATURE ANALYSIS (°C) 2-10 AUGUST 1972

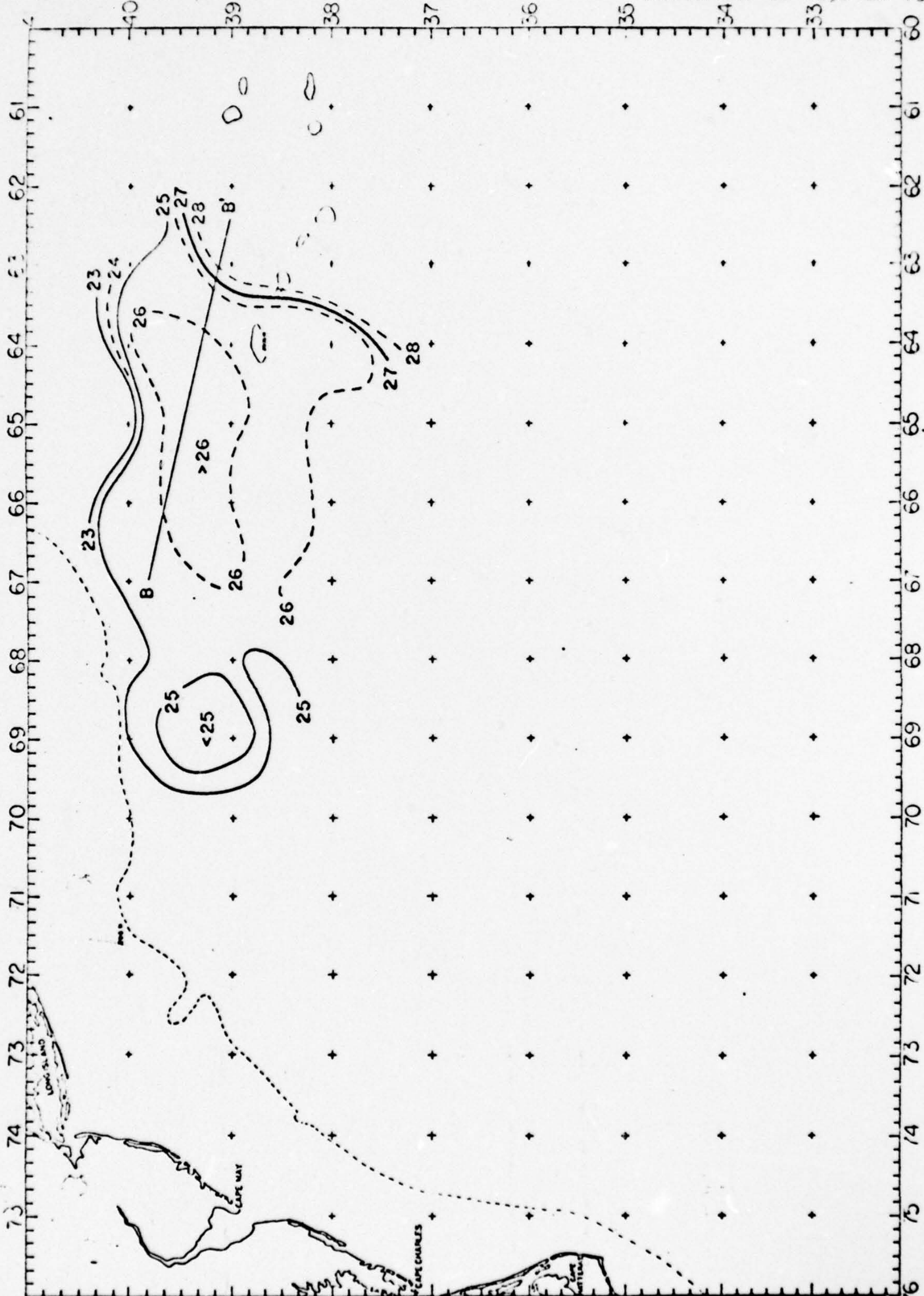


FIGURE 9a. SEA SURFACE TEMPERATURE ANALYSIS (°C) 12-16 AUGUST 1972

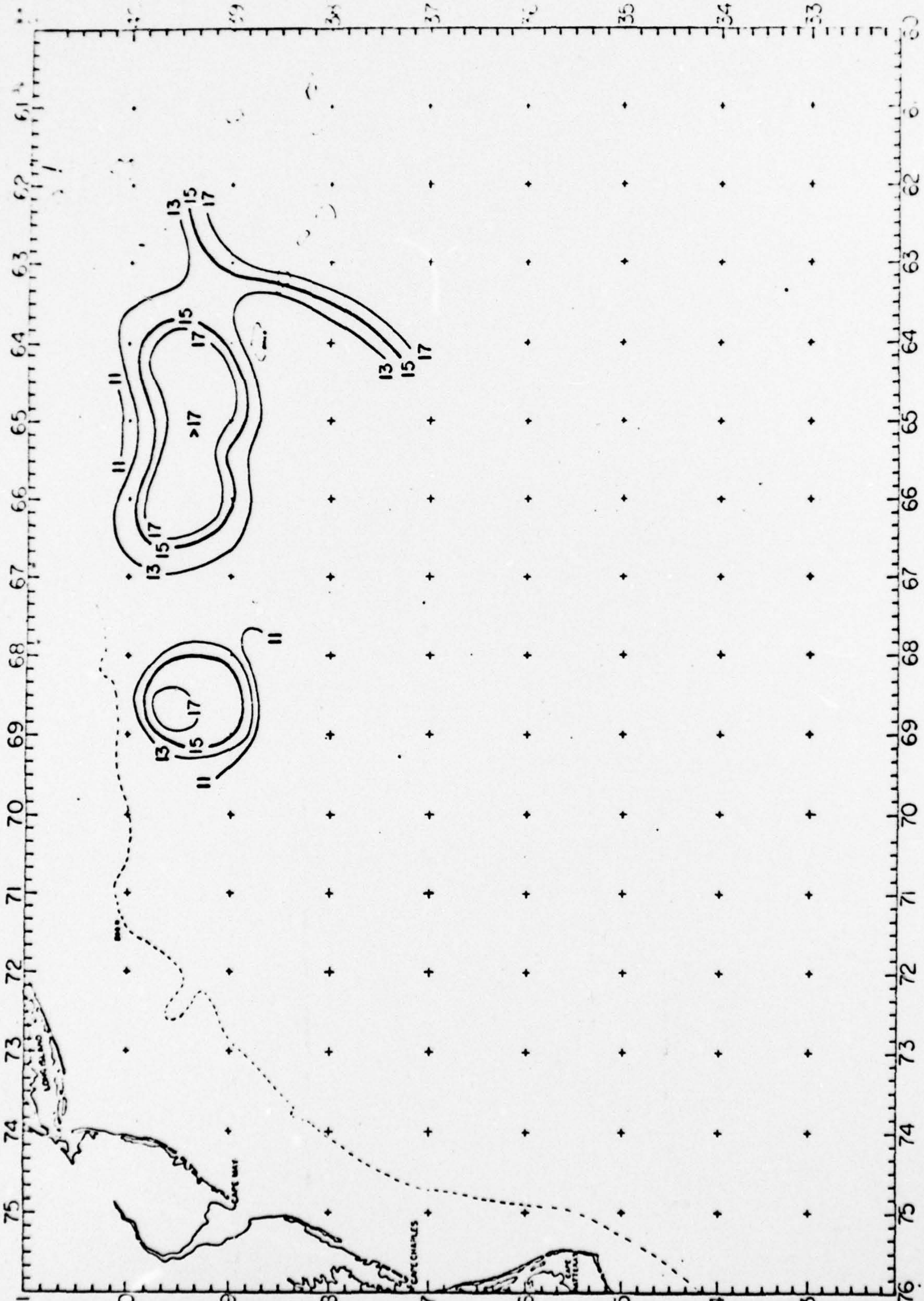


FIGURE 9b. 200 METER TEMPERATURE ANALYSIS (°C) 12-16 AUGUST 1972

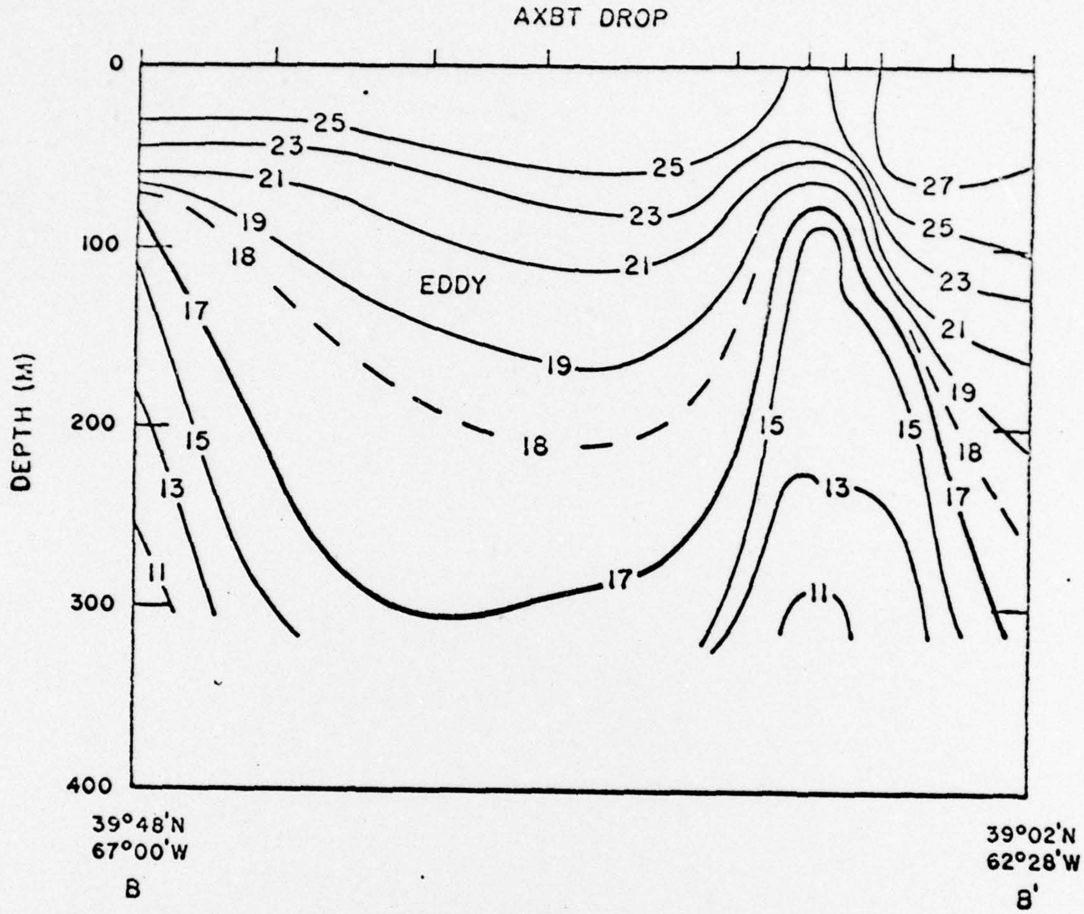


FIGURE 10. AXBT SECTION (°C) THROUGH A-72-2 16 AUGUST 1972

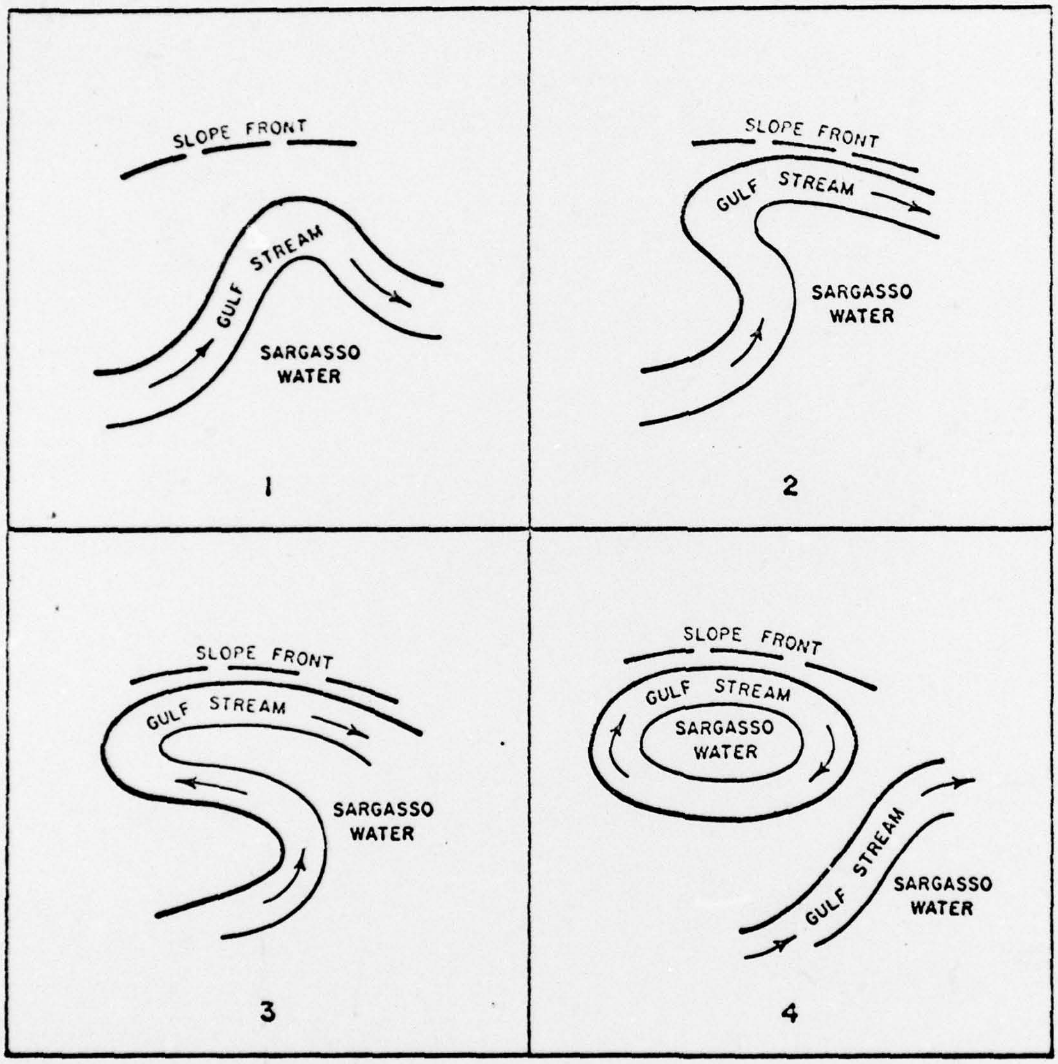


FIGURE 11. SCHEMATIC OF ANTICYCLONIC EDDY FORMATION

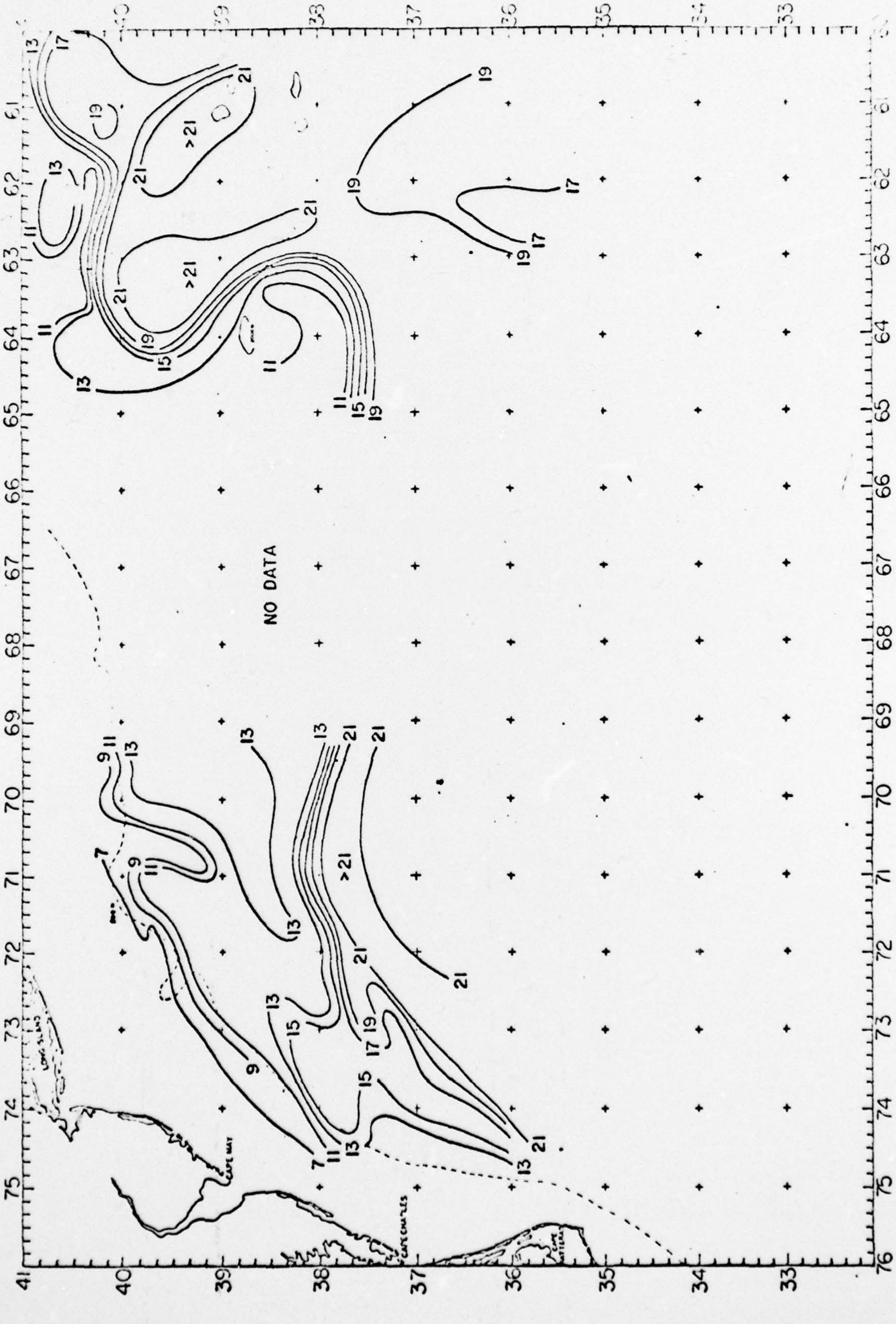


FIGURE 12a. SEA SURFACE TEMPERATURE ANALYSIS (°C) 12-13 FEBRUARY 1973

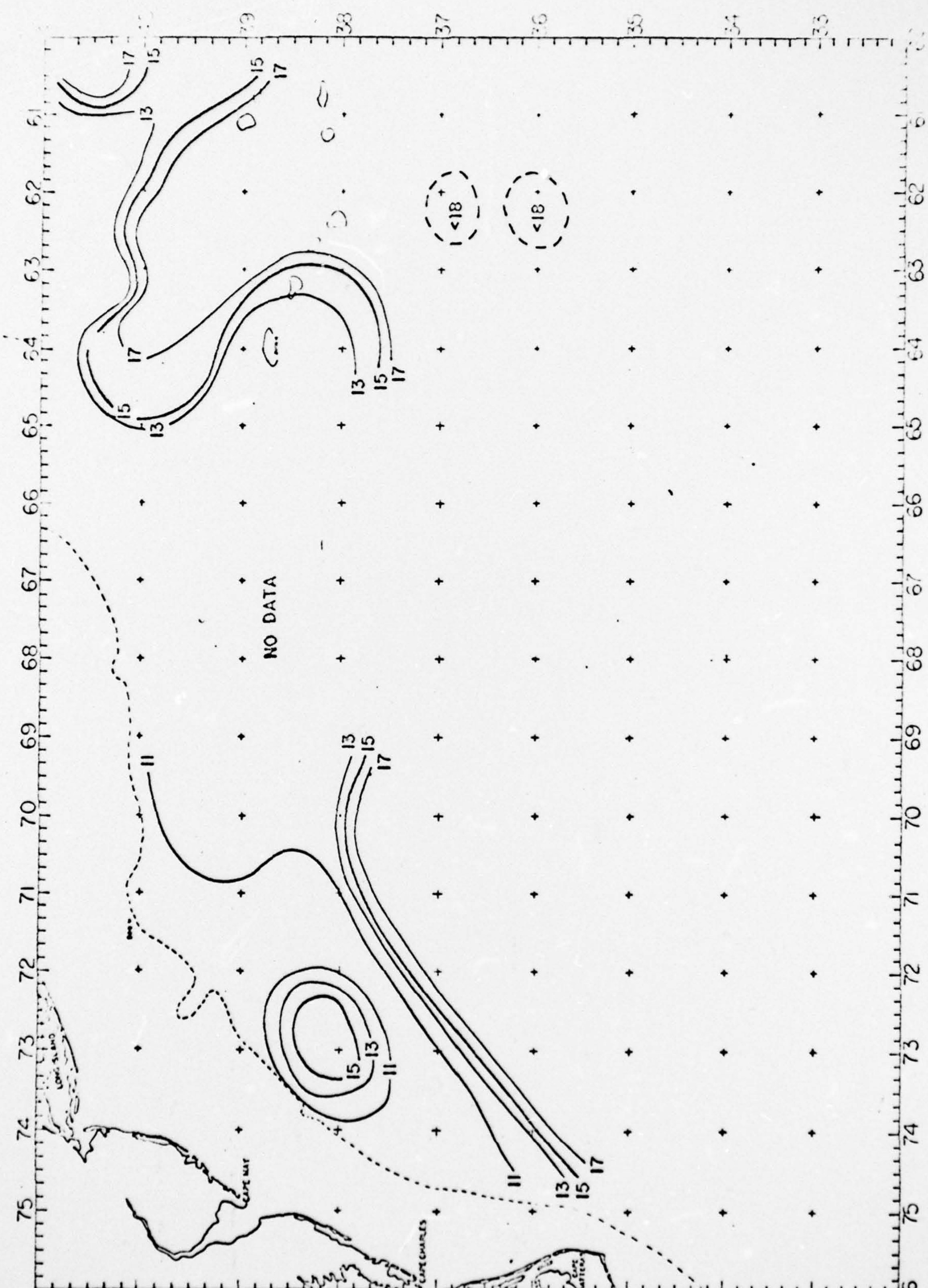


FIGURE 12b. 200 METER TEMPERATURE ANALYSIS (°C) 12-13 FEBRUARY 1973

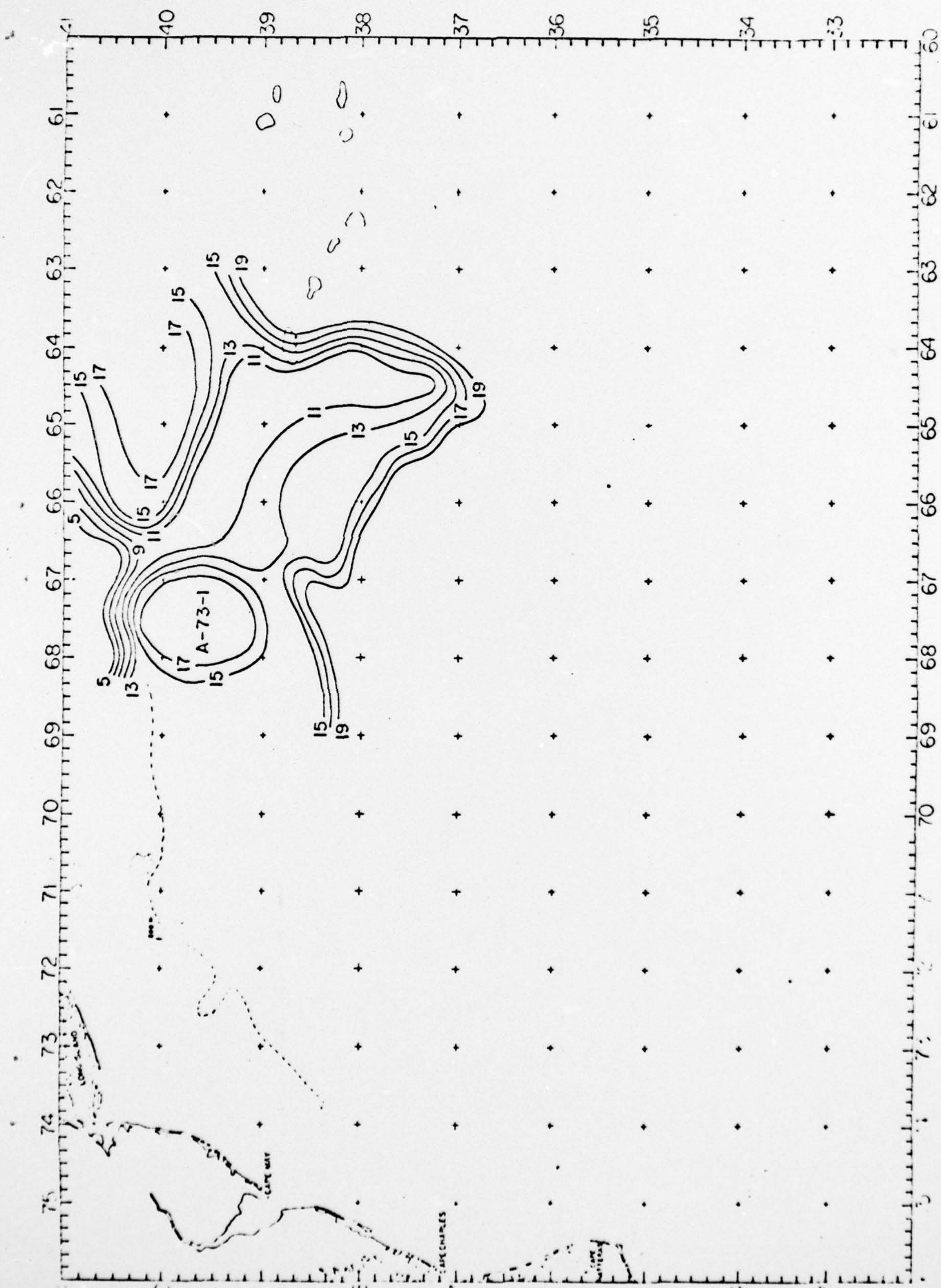


FIGURE 13a. SEA SURFACE TEMPERATURE ANALYSIS (°C) 1-2 MARCH 1973

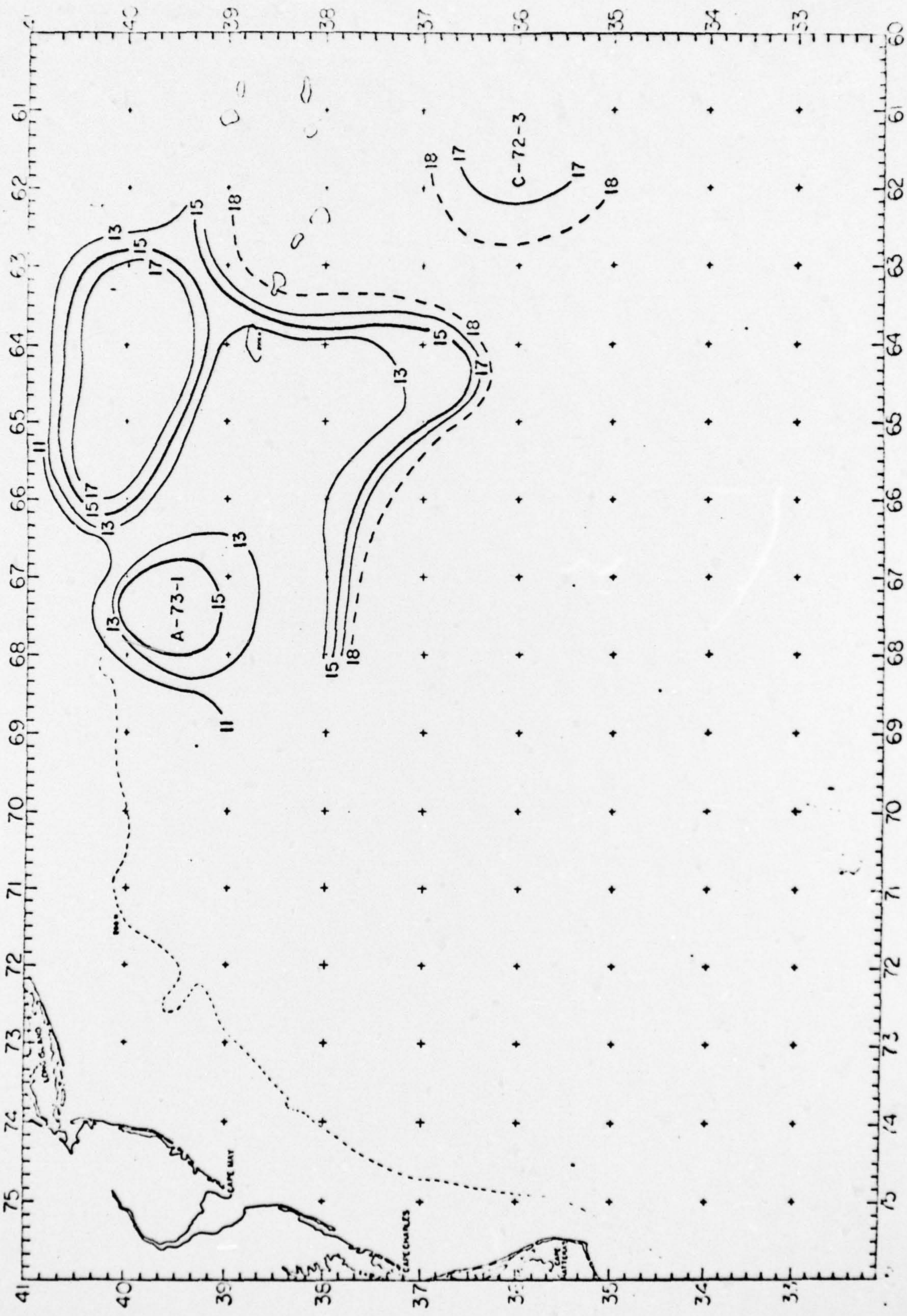


FIGURE 13b. 200 METER TEMPERATURE ANALYSIS (°C) 1-2 MARCH 1973

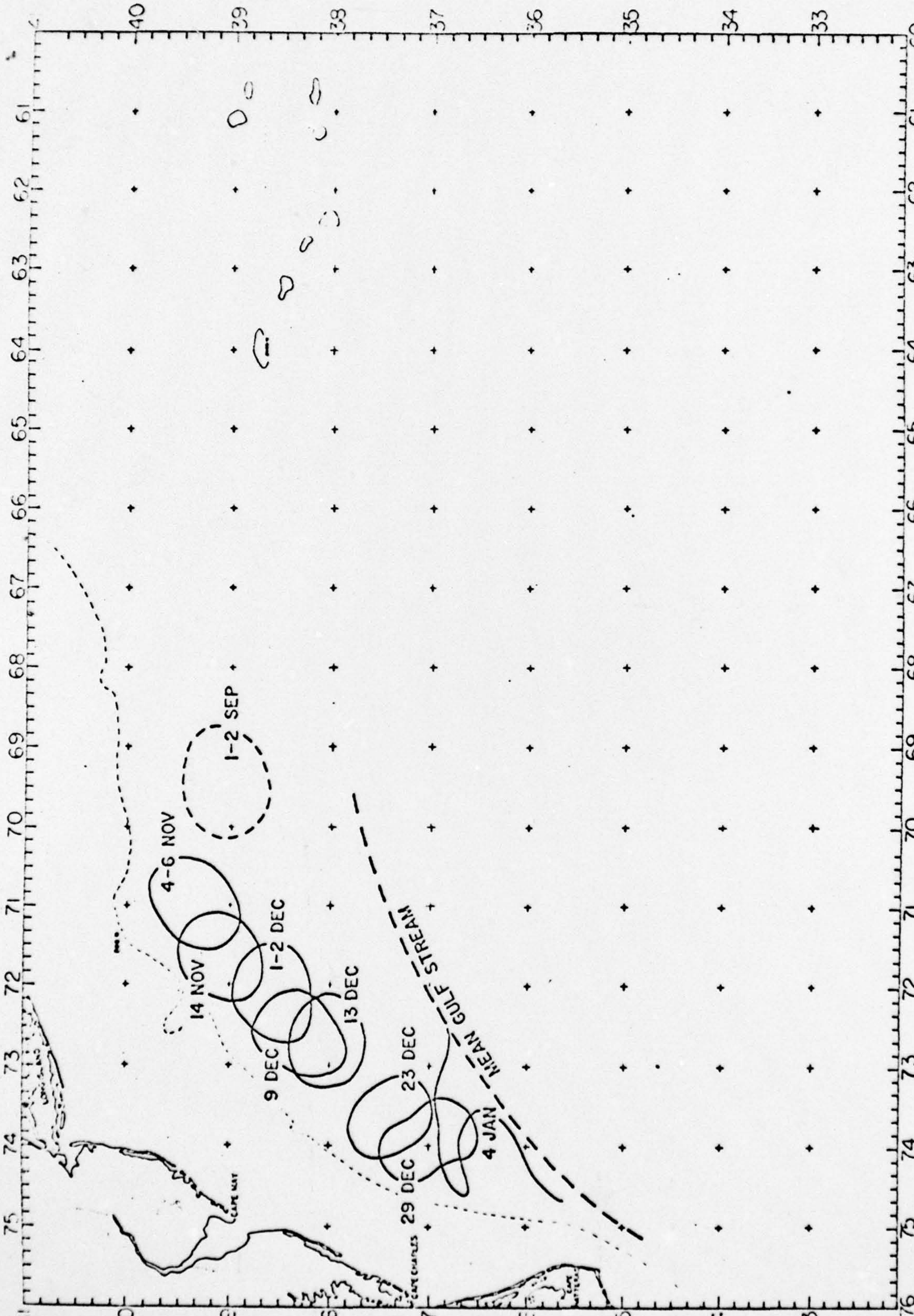


FIGURE 14. MOVEMENT AND RECAPTURE OF A-70-1 1 SEPTEMBER 1970 - 4 JANUARY 1971 (15°C AT 200 M)

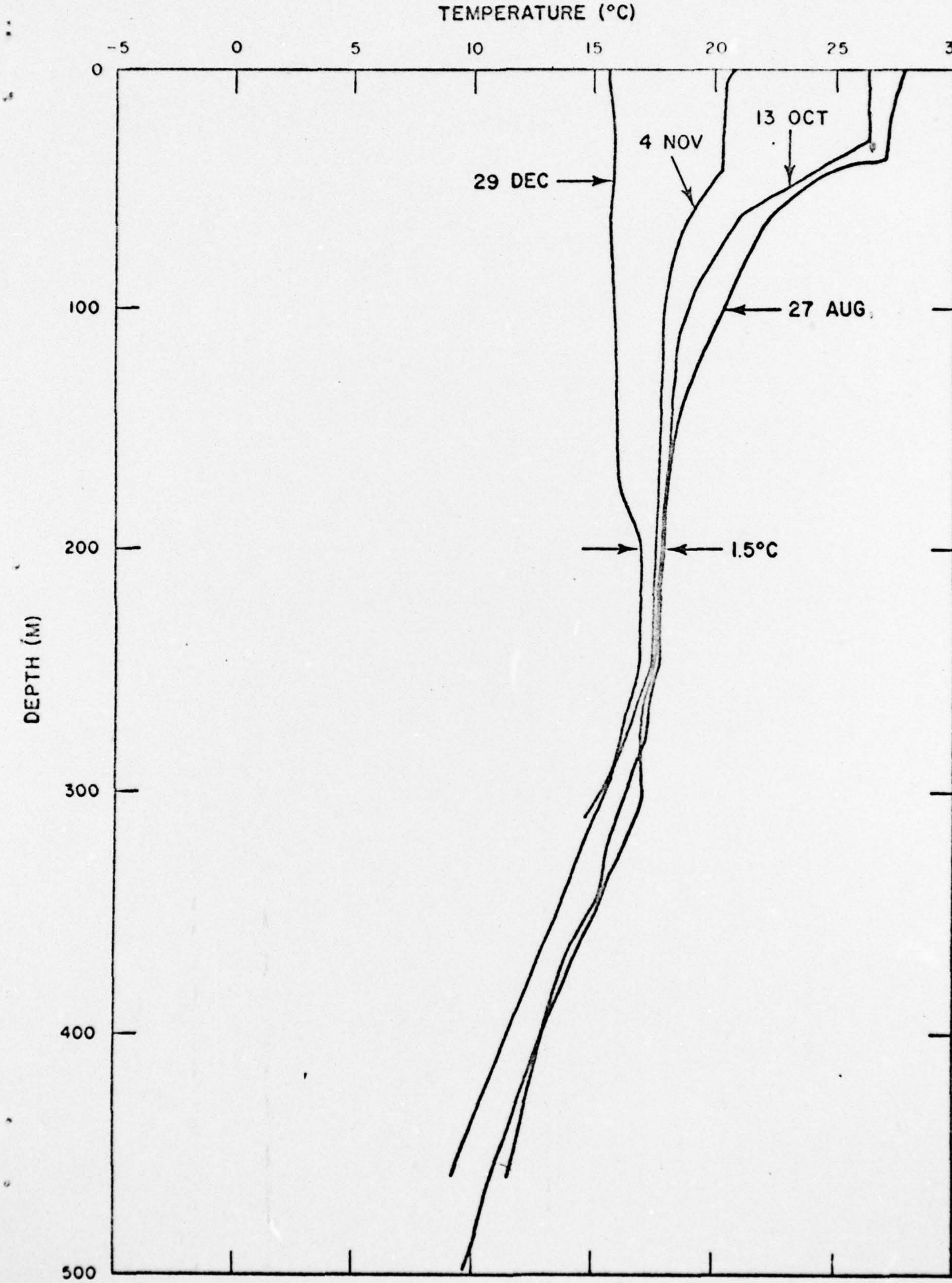


FIGURE 15. AXBTs TAKEN IN CORE OF A-70-1 27 AUGUST – 29 DECEMBER 1970

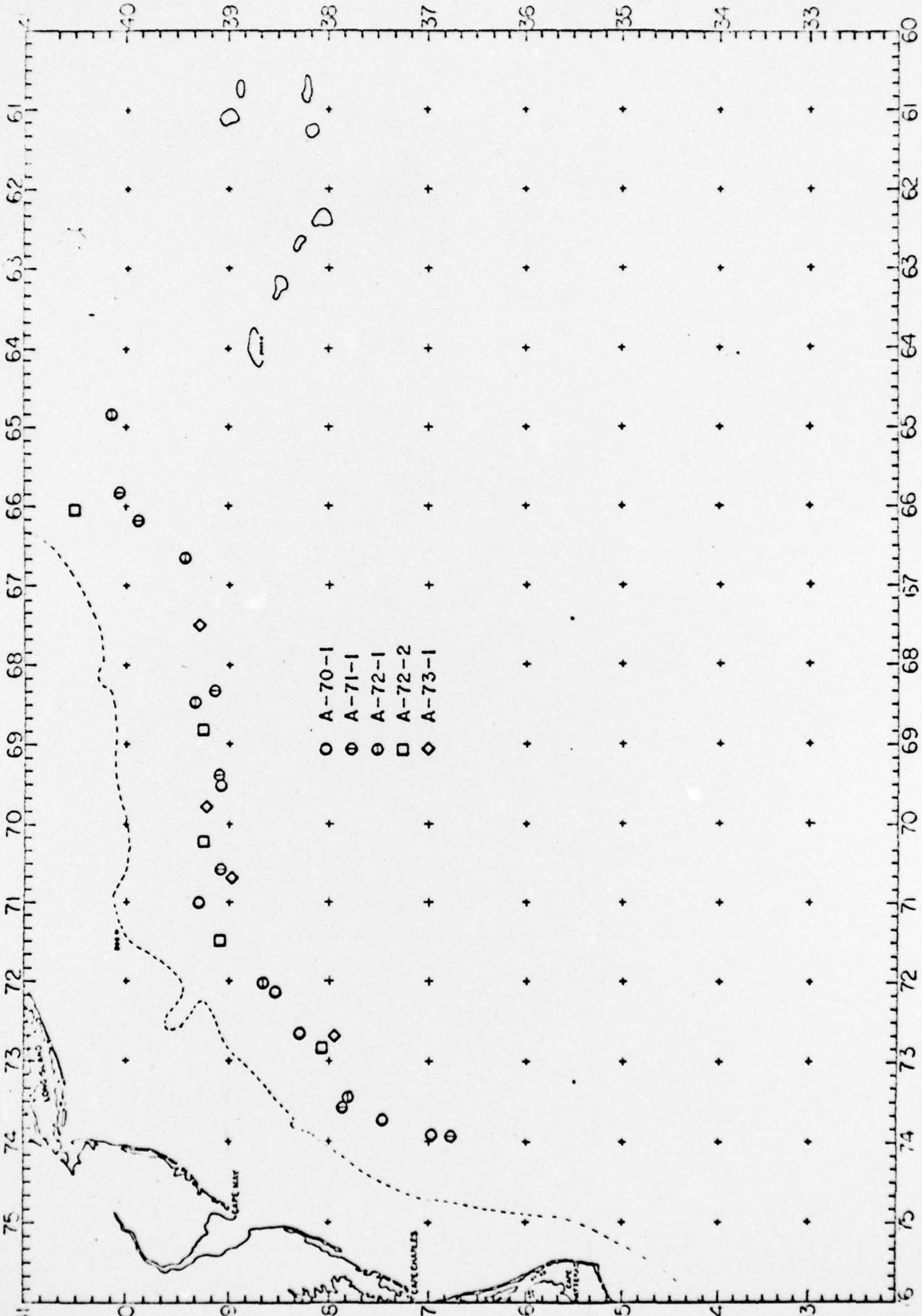


FIGURE 16. MOVEMENT OF FIVE ANTICYCLONIC EDDIES

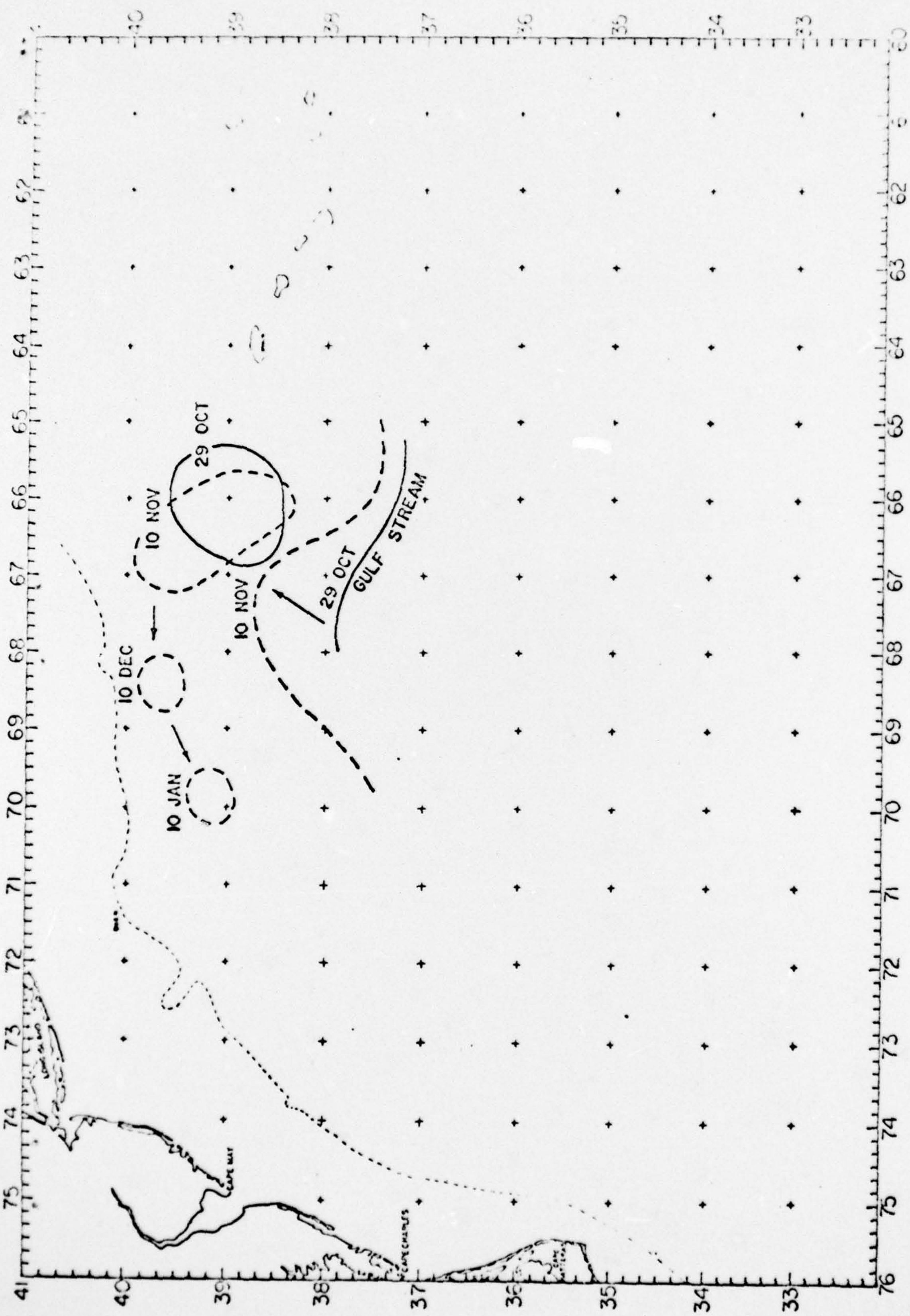


FIGURE 17. MOVEMENT OF A-71-2 AND RECAPTURE BY GULF STREAM MEANDER (15°C AT 200 M)

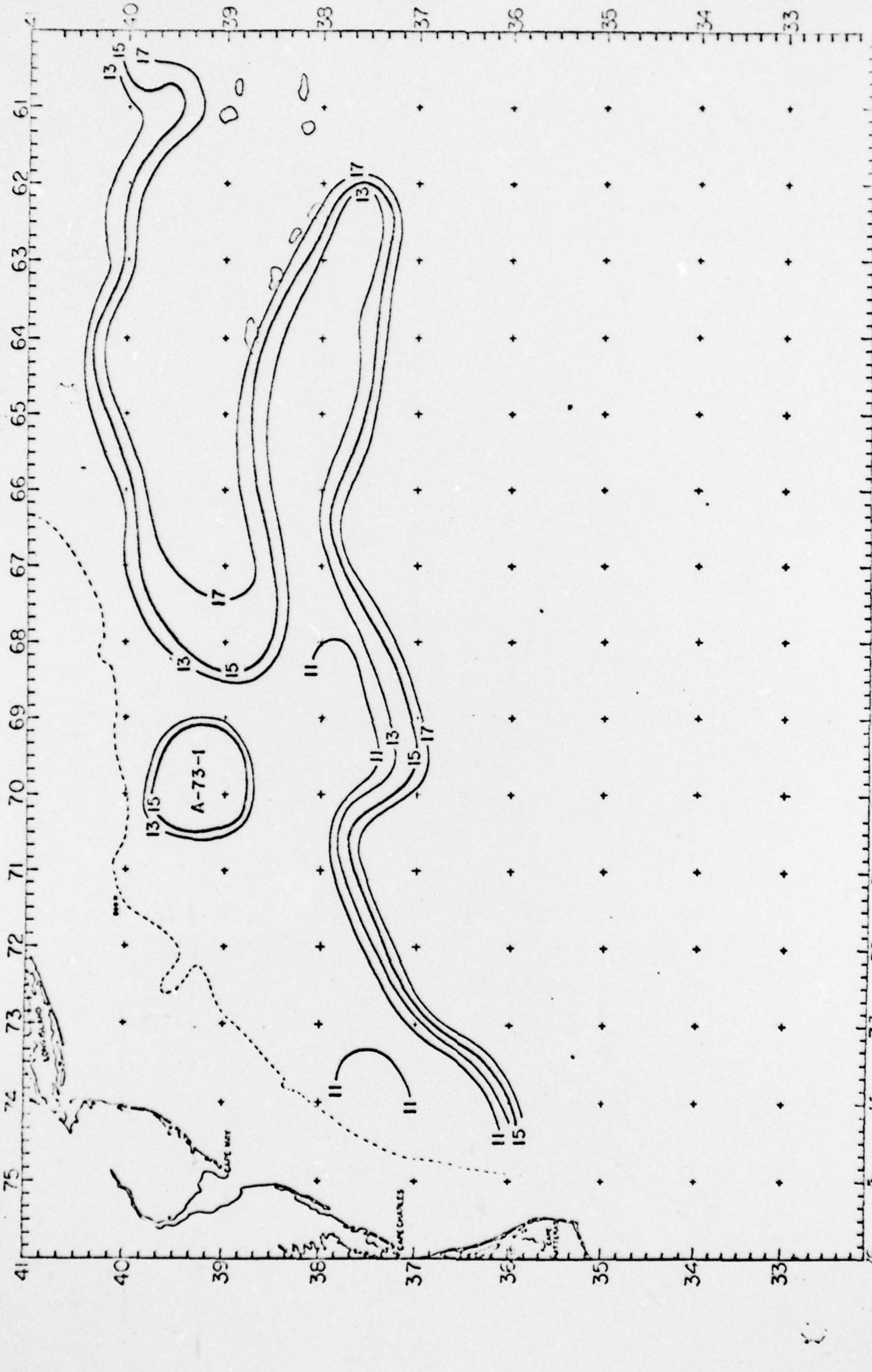


FIGURE 18. 200 METER TEMPERATURE ANALYSIS (°C) 3-4 MAY 1973

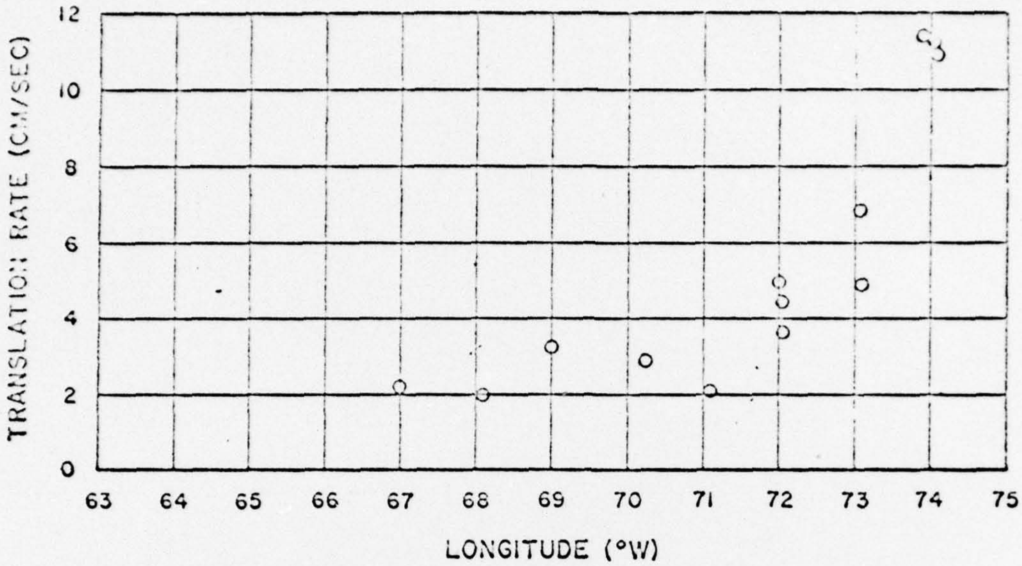


FIGURE 19. AVERAGE TRANSLATION RATES OF ANTICYCLONIC EDDIES

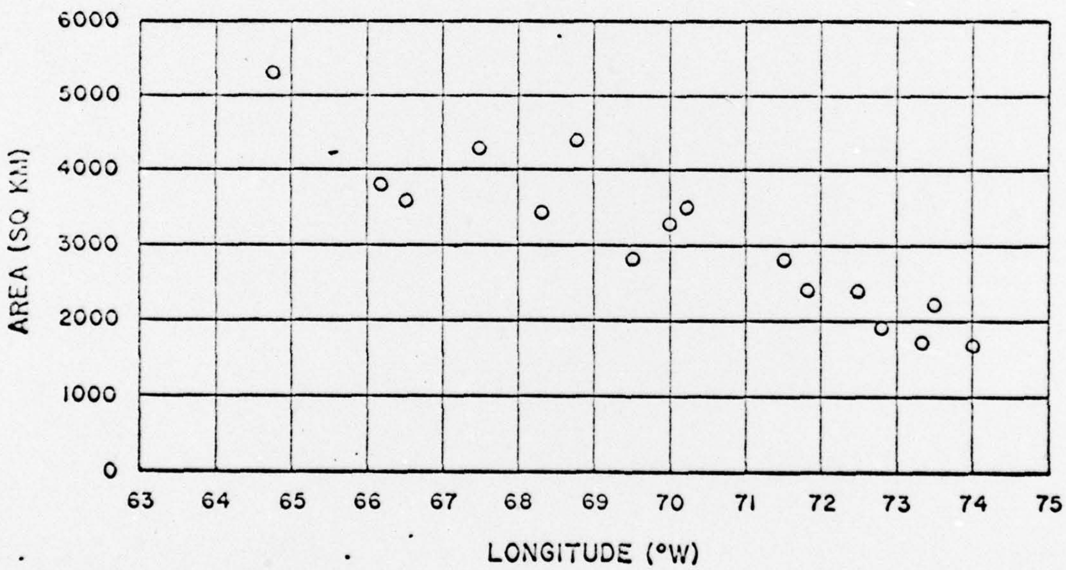


FIGURE 20. REDUCTION IN HORIZONTAL AREA OF ANTICYCLONIC EDDIES WITH WESTWARD MOVEMENT

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